

Isotope and chemical compositions of meteoric and thermal waters and snow from the greater Yellowstone National Park region

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Isotope and chemical Compositions of Meteoric and Thermal Waters and Snow from the Greater Yellowstone National Park Region

By Yousif K. Kharaka, James J. Thordsen *and* Lloyd D. White

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CONTENTS

ABSTRACT.....	1
INTRODUCTION	2
Description of Study Area	3
Regional Geology	3
Climate.....	4
METHODS AND PROCEDURES.....	5
Snow Samples.....	5
Field Procedures	6
Laboratory Measurements	6
Water Isotopes	6
RESULTS AND DISCUSSION	7
Chemical Composition of Cold Water and Snow.....	7
Isotope Composition of Cold Water and Snow	8
Controls on Cold Water Isotopes.....	9
Hydrothermal Fluid Discharges.....	10
Thermal Water and Gas Compositions.....	11
Origin and Evolution of Thermal Fluids.....	12
Hydrothermal fluids from the Mammoth system.....	14
CONCLUSIONS.....	15
ACKNOWLEDGEMENTS	15
REFERENCES CITED.....	16

Figures

1. Location of sampling sites for cold water, snow and thermal water in the greater Yellowstone National Park region.
2. Regional setting for the Norris-Mammoth corridor that extends from Yellowstone caldera through Mammoth Hot Springs to Corwin Springs Known Geothermal Resources Area. The thermal springs, including Narrow Gauge spring (NG) and wells, including Y-10 sampled are indicated (modified from Kharaka and others, 1991).
3. Location of sampling sites for cold water (groups AG, GG, and YP), snow, and thermal water in the Gardiner-Mammoth area and northern portion of Yellowstone National Park.
4. Location of sampling sites for cold water (groups GN, MR, SR and YP), snow, and thermal water in the western portion of the study area (Gallatin Range, Madison Range, Snake River Plain, and Yellowstone volcanic plateaus).
5. Location of sampling sites for cold water (groups AN, BT and YP), snow, and thermal water in the northeast portion of the study area (northern Absaroka Range & Beartooth Mountains).
6. Location of sampling sites for cold water groups AC and AD, in the southeast portion of the study area (southern Absaroka Range).
7. Generalized geologic map of the greater Yellowstone National Park study area. This map is modified from digital representation of the 1974 P.B. King and H.M. Beikman Map, by Schruben and others (1997).
8. Mean annual precipitation for the greater Yellowstone National Park study area based on 30-year average 1961-1990, from the digital PRISM mean annual map (National Atlas, 2002).

9. The stable isotope composition of 40 snow samples collected from the study area and their resultant Local Meteoric Water Line (LMWL) of $\delta D = 8.2 \delta^{18}O + 14.7$, which approximates the GMWL.
10. The stable isotope composition of cold-water samples collected in the study area. Note the departure of the linear fit from the GMWL, especially in samples with heavy isotopes.
11. Variation of *d*-parameter (see text) with altitude for the cold water samples. Note that the samples with *d*-parameter values <5, indicating significant evaporation, are mainly from low altitude areas.
12. Scatter plot of *d*-parameter (a) and altitude (b) vs. specific conductance (log scale) for cold water samples.
13. Scatter plot of *d*-parameter (a) and altitude (b) vs sulfate concentrations (log scale) for cold water samples.
14. The stable isotope composition for cold-water samples obtained from the nine (AD and AC samples are plotted together in top right) from geographic/physiographic regions.
15. Spatial distribution of *d*-parameter values for cold-water samples in the study area.
16. Spatial distribution of δD values for cold-water samples in the study area.
17. Spatial distribution of $\delta^{18}O$ values for cold-water samples in the study area.
18. Scatter plot of altitude vs. δD and $\delta^{18}O$ values for cold-water samples in the study area. Note the large scatter in the data points indicating complex relationship between altitude and water isotopes.
19. Cross section through study area showing altitude of sample sites, and δD and *d*-parameter values of cold-water samples vs. distance along line A-A' (fig. 16).
20. Scatter plot of altitude vs. $\delta^{18}O$ values for cold-water samples in the study area, compared to the predicted $\delta^{18}O$ values for winter and summer conditions at (see text for full explanation) Mammoth weather station (modified from Thordsen and others, 1992).
21. Total thermal water discharges from the Mammoth Hot Springs system for 1987-1994 (from Kharaka and others, 2000).
22. Scatter plot of δD vs. $\delta^{18}O$ values for thermal- and cold-water samples in the study area. Samples from acid sulfate springs controlled by boiling and condensation are delineated.
23. Distribution of the $^3\text{He}/^4\text{He}$ values relative to air (R/Ra) in thermal fluids from the Norris-Mammoth corridor. Note the high values for the Mammoth system and Norris Geyser Basin and the relatively low values in the intervening thermal areas (from Kharaka and others, 2000).

Tables

1. Description and location of cold water sample sites.
2. Description and location of snow sample sites.
3. Description and location of thermal springs and wells.
4. Chemical and isotopic data for cold water samples.
5. Chemical and isotopic data for snow samples.
6. Chemical and isotopic data for thermal water samples.

ABSTRACT

An intensive hydrogeologic investigation, mandated by U.S. Congress and centered on the Norris-Mammoth corridor was conducted by USGS and other scientists during 1988-90 to determine the effects of using thermal water from a private well located in the Corwin Springs Known Geothermal Resources Area, Montana, on the thermal springs of Yellowstone National Park (YNP), especially Mammoth Hot Springs. As part of this investigation, we carried out a detailed study of the isotopic and chemical compositions of meteoric water from cold springs and wells, of thermal water, especially from the Norris-Mammoth corridor and of snow. Additional sampling of meteoric and thermal waters from YNP and surrounding region in northwest Wyoming, southwest Montana and southeast Idaho was carried out in 1991-92 to characterize the distribution of water isotopes in this mountainous region and to determine the origin and possible recharge locations of thermal waters in and adjacent to the Park.

The δD and $\delta^{18}O$ values for 40 snow samples range from -88 to -178‰ and -12.5 to -23.9‰ , respectively, and define a well constrained line given by $\delta D = 8.2 \delta^{18}O + 14.7$ ($r^2 = 0.99$) that is nearly identical to the Global Meteoric Water Line. The δD and $\delta^{18}O$ values of 173 cold water samples range from -115 to -153‰ and -15.2 to -20.2‰ , respectively, and exhibit a similar relationship although with more scatter and with some shift to heavier isotopes, most likely due to evaporation effects. The spatial distribution of cold-water isotopes shows a roughly circular pattern with isotopically lightest waters centered on the mountains and high plateau in the northwest corner of Yellowstone National Park and becoming heavier in all directions.

The temperature effect due to altitude is the dominant control on stable water isotopes throughout the region; however, this effect is obscured in narrow 'canyons' and areas of high topographic relief. The effects due to distance (i.e. "continental") and latitude on water isotopes probably are relatively minor and difficult to resolve from the major controls. The data indicate that the groundwater are derived predominantly from cold, isotopically light winter precipitation, and that the isotope values of groundwater from elevations above about 2.5-3.0 km in the Gallatin and northern Absaroka Ranges are light enough (The $\delta D \geq -149\text{‰}$) to be the presumed recharge water for the hydrothermal system in the Park. However, estimation of the present-day volume of this recharged, isotopically light water indicates that it is not adequate to supply the high ($3\text{-}4 \text{ m}^3/\text{s}$) thermal water discharges from YNP, and cooler temperatures at the time of recharge would be required. The volume of meteoric water with δD values lighter than -145‰ may be adequate for recharging the hydrothermal system, and this may be a more plausible value than the -149‰ originally calculated from data that are subject to moderate uncertainties.

INTRODUCTION

Yellowstone National Park (YNP) is unrivaled for the abundance and diversity of its hydrothermal features, including geysers, fumaroles, mud pots and thermal springs (e.g., White and others, 1988; Smith and Siegel, 2000). These extraordinary features are distributed throughout the entire 9,000-km² area of the Park, but are concentrated in several geyser basins located within the 0.6-Ma Yellowstone caldera and in the Norris-Mammoth corridor (figs. 1-3). The Norris-Mammoth corridor (fig. 2) is a complex north-south subsidence structure, extending ~40 km from the Yellowstone caldera to the Corwin Springs Known Geothermal Resources Area (KGRA) located north of the Park in Montana (e.g., Pierce and others, 1991). The Norris-Mammoth corridor contains the only major alignment of volcanic vents and hydrothermally altered areas outside the caldera; the 13 rhyolitic and basaltic vents have ages of 400-80 ka (Hildreth and others, 1991).

The hydrothermal features in YNP are the surface manifestations of very high fluid discharges that include, thermal water, water vapor and gases, especially CO₂ (Fournier, 1989; Kharaka and others, 2000; Werner and others, 2000). Thermal water discharges from YNP have been estimated to average a total of about 3-4 m³/s (Fournier, 1989; Kharaka and others, 2000). The exceptional hydrothermal features of YNP are the result of a favorable combination of climatic and geologic factors, including a huge magmatic heat source that is present at a relatively shallow depth of 4-8 km beneath the 0.6 Ma Yellowstone caldera (Wicks and others, 1998), abundant supplies of recharge water primarily from melting snow and frequent seismic activity that creates new fractures and reopens clogged channels for fluid flow (Fournier, 1989; Kharaka and others, 2000). The shallow magmatic heat driving this hydrothermal system is associated with a deep-mantle plume, a hotspot, that is presently centered beneath the Yellowstone caldera and is responsible, during the last 2.2 Ma, for the huge eruptive volume (~6,000 km³) of rhyolitic ash-flow tuffs and lavas, covering an area of about 17,000 km² in and adjacent to YNP (e.g. Wicks and others, 1998; Smith and Siegel, 2000; Christiansen, 2001).

An intensive hydrogeologic investigation, mandated by U.S. Congress and centered on the Norris-Mammoth corridor (fig. 2), was conducted by the U.S. Geological Survey (USGS) during 1988-90, in collaboration with the National Park Service and the Argonne, Lawrence Berkeley and Los Alamos National Laboratories, to determine the effects of using thermal water from a private well located in the Corwin Springs, ~3 km north of the Park, on the thermal springs of YNP, especially Mammoth Hot Springs (Sorey, 1991). We have conducted major additional hydrologic and geochemical studies in the corridor and the greater Yellowstone region, especially in the Gallatin and Absaroka Ranges, in order to improve understanding of the origin and evolution of thermal waters in the area. The bulk of the physical, chemical and isotope data for the thermal springs, as well as conclusions and recommendations regarding hydrogeologic connections in the Norris-Mammoth corridor and various thermal features in the Corwin Springs KGRA, are reported in chapters in Sorey (1991), especially in Kharaka and others (1991). Additional results and interpretations regarding the hydrothermal system in the Norris-Mammoth corridor have been reported in Bullen and Kharaka (1992), Mariner and others (1992), Thordsen and others (1992), Sorey and Colvard (1997) and Kharaka and others (1992, 2000).

In this report we present previously unpublished chemical and/or isotope data for 173 water samples from cold springs, shallow cold wells and 40 snow samples collected from the greater Yellowstone National Park area. For this study, we emphasize the sampling of cold wells and cold perennial springs, as opposed to streams, rivers and precipitation favored by Rye and Truesdell (1993). Even though each of the two approaches have limitations, wells and springs were selected, because they yield time-integrated samples of precipitation with relatively uniform isotope values that usually are better representatives of local meteoric water (White and others, 1990; Kharaka and Thordsen, 1992). Samples of freshly precipitated snow were collected, because their isotopes provide better data for establishing the regional meteoric water line (Thordsen and others, 1992; Clark and Fritz, 1997). Although some discussion and interpretation are given for the distribution of cold-water isotopes, the

primary purpose is to make the data available to interested researchers and other scientists. Data for all the thermal waters collected by us, including for samples from sites located outside the Norris-Mammoth study area reported in Kharaka, and others (1991) are also presented. Results are used as a basis for discussing the origin and evolution of thermal waters, especially in the Norris-Mammoth corridor.

Description of Study Area

The study area encompasses about 40,000 km², mostly in the northwest corner of Wyoming and portions of southwest Montana and east-central Idaho (fig. 1). Most sampling sites are located in YNP, especially the Norris-Mammoth corridor; others extend 50 to 100 km outside the Park boundaries in all directions, except the far southwest (figs. 1-6). The area is characterized by a high volcanic plateau roughly centered on YNP with an average altitude of about 2400 m, which is cut by deep, narrow river canyons and wide valleys. The highest elevation within the Park is Eagle Peak (3500 m) near the southeastern corner, and the lowest elevation is in the northwest corner near Mammoth (1600 m). The volcanic plateau is nearly encircled by prominent mountain ranges, including the Gallatin and Madison Ranges (northwest), the northern Absaroka Range and Beartooth Mountains (north-northeast), the southern Absaroka Range (east-southeast) and the Teton Range (south). All of these ranges have mountains that exceed altitudes of 3000 m; to the southwest, however, the plateau descends gradually onto the Snake River plain to below 2000 m (figs. 1 and 4).

The major watersheds inside the Park are the Snake River (southwest) that drains into the Pacific Ocean, and the Yellowstone (north and east-central), Madison (west), and Gallatin (northwest) rivers that drain into the Atlantic Ocean via the Gulf of Mexico. The Continental Divide defines the boundary between these watersheds. Outside the Park, the Wind River drains the southeast portion of the study area, near Dubois; and the Clarks Fork River, Rock Creek and Stillwater River drain the northeastern portion of the study area (Beartooth Mountains).

Regional Geology

The Yellowstone Plateau volcanic field (fig. 7) is one of the largest Quaternary and latest Pliocene silicic centers in the world (Christiansen, 2001). During the last 2.2 Ma an eruptive volume of about 6,000 km³ of ash-flow tuffs and rhyolitic lavas have covered an area of about 17,000 km² (Christiansen, 1984; Hildreth and others, 1991). The igneous rocks of the field consist dominantly of rhyolites and subordinate basalt, with no intermediate compositions. The rhyolites comprise numerous lava flows and three major sheets of welded ash-flow tuff, with eruptions causing large caldera collapses at 2.0, 1.3 and 0.6 Ma (Hildreth and others, 1991). Even younger volcanic rocks are present in the Park, including the 13 rhyolite and several basaltic vents with ages of 400-80 ka, that are present in the Norris-Mammoth corridor (Hildreth and others, 1991).

The youngest rocks in the Park are present in the northwest sector of YNP at Mammoth Hot Springs, which is considered the world's most spectacular thermal area of active travertine precipitation. Massive amounts of travertine, with ages from about 400 ka to present, have and are being precipitated over a large area from nearly 100 hot springs scattered over a score of steplike terraces covering a large area, ~1 km wide and 4 km long (Pierce and others, 1991; Kharaka and others, 1991). A thermal mantle plume hypothesis is currently the preferred model for the origin of the Yellowstone province as well as the eastern Snake River Plain volcanic field (Morgan, 1973; Pierce and Morgan, 1990). In this model a deep mantle hotspot, now centered beneath Yellowstone, was initiated 16 Ma. The track of this hotspot is defined by centers of caldera-forming volcanism that have migrated 700 km northeastward along the Snake River to the Park (Christiansen, 2001).

Volcanic activity in and near YNP was also widespread in the early Eocene (~50 Ma), when several large volcanoes erupted intermittently giving rise to the volcanoclastic and volcanic rocks of the Absaroka Volcanic Supergroup (fig. 7). The Absaroka Volcanics are predominantly andesites, with minor amounts of basalt and they cover most of the Absaroka and Washburn Ranges and part of the Gallatin Range as well as several smaller areas in the Park (Hildreth and others, 1991). The Absaroka Supergroup originated as volcanic arcs related to the westward movement of the North American plate and the subduction of the Pacific and related plates (Christiansen, 2001, and references therein).

The oldest rocks in YNP are the Precambrian basement rocks, about 2.7 billion yr, comprised of gneisses and schists. These rocks are exposed only in the northern part of the Park, where they form the central cores of some mountain ranges such as the Gallatin Range. Precambrian granitoids are also exposed in the Beartooth Mountains (fig. 7) and are present in the Park at relatively shallow depths beneath the sedimentary and volcanic rocks (Pierce and others, 1991). The sedimentary section consists of Cambrian through Cretaceous marine sandstones, shales and limestones, including the Mississippian Mission Canyon Limestone, which is an important regional aquifer (Downey, 1984; Plummer and others, 1990). Glacial and other surficial deposits thinly mantle the bedrock (fig. 7) over large areas in the region (Pierce, 1979).

Climate

The mountainous terrain of the study area is the main control on its climate. The Park is situated about 600 km from the Pacific Ocean in the mid-latitudes and near the southeast end of the Rocky Mountain chain, which extends far to the northwest through Idaho, Montana and Canada. The study area receives about 75% of its annual precipitation as winter snow from air masses originating in the North Pacific Ocean. Pacific air masses either pass over the high mountains northwest of the Park or move eastward and gradually ascend along the Snake River Plain onto the Yellowstone plateau. The region is also influenced during the winter by Arctic cold air masses and during the summer by warm moist air masses originating in the Gulf of Mexico (Dirks and Martner, 1982, Despain, 1987).

Despain (1987) describes the Yellowstone region as having two principal climatic types: 1) The interior low plateaus and valleys, characterized by a spring peak in precipitation, similar to the Great Plains climate; and 2) the western plateaus and the northern (Gallatin, Madison, and Washburn ranges) and eastern (Absaroka) mountains of the Park, characterized by a winter peak in precipitation, similar to the West coast and mountains of Idaho and northwestern Montana. The largest amounts of precipitation (about 200 cm) fall during winter on the high plateaus located in the southwest part of the Park, because Pacific air masses that approach from the west along the Snake River plain are orographically lifted as they ascend the plateau. This results in large snow accumulations on these regions, whereas the central plateau, situated in the rain shadow of the surrounding mountains, receives lower (about 70 cm) precipitation (fig. 8).

Long-term temperature data from 12 climatic stations show a strong relationship between temperature and elevation. Calculated spring and summer lapse rate from these stations is $-9.7^{\circ}\text{C}/\text{km}$, which is close to the dry adiabatic rate; the winter lapse rate of $-5.3^{\circ}\text{C}/\text{km}$ is much lower due probably to temperature inversions (Despain, 1987; Thordsen and others, 1992). During winter months, warmer western air encounters cooler eastern air along the continental divide, resulting in heavy precipitation. Temperature inversions are common, especially in the larger valleys, occurring on more than 40% of the days during seven months of the year. Inversions that persist into the afternoon are most common during the winter months, occurring at ~50% of the days in December.

METHODS AND PROCEDURES

Field investigations conducted in 1988 through 1992 resulted in a total of close to 300 samples from 228 different sites (figs. 1-6). A total of 173 samples were obtained from 136 different cold springs, seeps and shallow cold wells, 40 samples were obtained as either snow cores or snow grabs, 58 samples were collected from 37 thermal sites (figs. 1-6). Many of the strategically located thermal sites and some of the cold-water sites located in the Norris-Mammoth corridor were sampled several times (up to five) to ascertain the seasonal variability (Kharaka and others, 1991). The methods used in sample collection, preservation and field and laboratory determinations of the chemical components and isotopes are discussed by Kharaka and others (1990, 1991) and by Thordsen and others (1992).

The cold water sampling sites are concentrated in the Gallatin and northern Absaroka Ranges (figs. 1-4) near the northwest corner of the Park (Mammoth-Gardiner area), because that area was postulated by Truesdell and others (1977) as a possible recharge location for the hydrothermal system in the Park. Sample sites also are concentrated in the mountainous areas to the north and northwest, along the Snake River Plain to the west, and at the south end of the Absaroka Range to the southeast. For cold water sites, an effort was made to sample perennial springs having good discharge rates (Ls/min) and, whenever possible, cold water wells. The measured water temperature and conductance and measured or estimated discharge were used to select springs and seeps for sampling. Springs and seeps with obvious contamination and evaporation effects were avoided. Springs and seeps located below lakes and water bodies, that may have been the source for water, were also avoided.

Most of the springs sampled are shown on the 7.5-minute USGS topographic maps. Springs located on private lands often are modified and diverted by pipes to new locations for cattle or domestic use; samples from such sites were obtained as close to the spring source as possible. Where springs and seeps were located close to streams and drainage lines, samples from the main channels were excluded. Most of the sampled groundwater wells are located on public campgrounds or on private lands close to houses and other structures. Inside the YNP boundaries and particularly in the vicinity of thermal areas, care is needed to avoid springs that may contain a thermal water component. These mixed springs usually can be distinguished in the field because they commonly have higher temperature and conductance (Thordsen and others, 1992).

Snow Samples

Snow samples were collected (figs. 1, 3-4) during May, 1991 from three localities in the study area: 1) the Beehive basin, a small catchment basin (of ~6 km²) in the Madison Range, near the Big Sky ski area (fig. 4); 2) Mt. Washburn, near the center of YNP (fig. 3); and 3) Beartooth Pass area, in the Beartooth Mountains (fig. 5). These localities were selected because: 1) they were easily accessible during the early spring (i.e. roads were open) while still having a substantial winter snow pack; 2) several cold water sites were established at each locality, several of which were sampled before and after the 1991 snowpack; 3) these localities provide a reasonably good west-to-east cross section through the northern portion of the study area. In addition to these 3 localities, a single snow core was obtained near an unnamed spring northeast of the town of Gardiner (site AG-5, fig. 3). Also, a suite of 9 snow samples was collected on 14 September, 1991 from the central part of YNP, between Norris, Mt. Washburn and Grant Village, from a snowstorm that started the previous night and continued into the morning of September 14.

For a particular location, 3 to 5 cores were taken, depending on the snow depth, using a ~4 cm inner diameter PVC pipe. The snow was "double bagged" in resealable plastic bags (~4 L), and allowed to slowly thaw, usually overnight. When completely melted, two 20-ml isotope bottles were filled and sealed with polyseal caps (Thordsen and others, 1992). Additional water was filtered through 0.1 µm

Millipore filters using compressed air. Acidified and unacidified aliquots were collected, as was the case for water samples, for chemical analysis using standard techniques (Kharaka and others, 1991).

Field Procedures

The methods used in sample collection, preservation and field and laboratory determinations of chemical components and isotopes are detailed in Kharaka and others (1990), Kharaka and others (1991), and Thordsen and others (1992). Water temperatures were usually measured, but discharges usually were only estimated. However, since several field teams were involved in sampling during the study, discharge estimates have high (factor of two) uncertainties. Most field chemistry was performed in a mobile laboratory equipped with pH meters, a spectrophotometer, and filtration, titration and other field equipment. Field determinations, especially on thermal samples included conductance, pH, alkalinity, H₂S and NH₃. Raw water samples were usually filtered through a 0.1 µm filter using either compressed nitrogen or compressed air as the pressure source. Filtered samples were stored in high-density polyethylene bottles prerinsed with deionized water for anions, and prerinsed with 5% nitric acid (HNO₃) then deionized water for metals and silica. For water isotopes, two 20-ml glass bottles with polyseal caps were filled with raw water. Samples for solute isotopes, organic compounds, silica and other chemical components, when required, were collected and diluted and/or preserved by procedures detailed in Kharaka and others (1991).

Laboratory Measurements

The water and snow samples were analyzed at USGS Water Resources laboratories in Menlo Park, CA. Concentrations of calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), and lithium (Li) were determined by flame atomic-absorption spectrometry (AAS) using a double-beam atomic absorption spectrophotometer. Chloride (Cl), bromide (Br), nitrate (NO₃), phosphate (PO₄), and sulfate (SO₄) were determined by ion chromatography (IC). Barium (Ba), boron (B), iron (Fe), manganese (Mn), silica (SiO₂) and strontium (Sr) were determined by inductively coupled plasma mass spectrometry (ICP-MS).

The reported concentrations for major cations and anions carry an uncertainty of ±3%. Precision values for minor and trace chemicals are generally ±5%, but could reach ±10% for values close to detection limits (Kharaka and others, 1991).

Water Isotopes

Water isotopes were determined in the USGS Stable Isotope Laboratory in Menlo Park. Water isotopes are reported in δ-values that are expressed in parts per thousand (per mil, ‰) relative to Standard Mean Ocean Water (SMOW). In the case of oxygen, the equation used is:

$$\delta^{18}\text{O} = \left(\frac{(^{18}\text{O} / ^{16}\text{O})_{\text{sample}}}{(^{18}\text{O} / ^{16}\text{O})_{\text{SMOW}}} - 1 \right) \times 10^3,$$

and in the case of hydrogen, the equation used is:

$$\delta^2\text{H} = \left(\frac{(^2\text{H} / ^1\text{H})_{\text{sample}}}{(^2\text{H} / ^1\text{H})_{\text{SMOW}}} - 1 \right) \times 10^3.$$

The Standard Deviation of reported values for samples are ±0.2‰ for δ¹⁸O and ±2‰ for δD.

RESULTS AND DISCUSSION

Data are organized into tables of general information (tables 1-3) and physical, chemical and isotopic data (tables 4-6). General information includes location and description of sample sites for cold water (table 1), snow (table 2), and thermal water (table 3). The physical, chemical and isotope data for cold water, snow and thermal water samples are presented in tables 4-6, respectively.

The cold meteoric water sites (tables 1 and 4) are organized into 10 groups, based on geographic region and the local physiography and drainage. This grouping of sample sites is useful for describing and evaluating the relative influences of the climatic and geographic/physiographic controls on the isotopic composition of cold waters. These groups, described below, are assigned a 2-letter abbreviation that expresses the mountain range or other distinguishing physiographic features such as the nearest geographic city/town (e.g. Gallatin Range – Gardiner-Mammoth area = GG). Sample sites in each group are assigned a unique ID in order of the date of first sample at that site. A number of strategically located and easily accessible sites were resampled (16 total), some as many as 4 times during the course of the study, in order to evaluate typical seasonal and annual variations.

The 10 regional groups for the cold-water samples are listed below:

- (GG) Gallatin Range – in vicinity of Gardiner-Mammoth and the Corwin Springs KGRA
- (AG) Absaroka Range – in vicinity of Gardiner, Mammoth and the Corwin Spring KGRA
- (AN) Absaroka Range – northern area
- (AR) Absaroka Range – northeast area (Beartooth Mountains) near Red Lodge, MT
- (AC) Absaroka Range – east of YNP, near Cody, WY
- (AD) Absaroka Range – southern region, near Dubois, WY
- (GN) Gallatin Range – northern portion of Gallatin Range
- (MR) Madison Range – and mountain region northwest of YNP
- (YP) Yellowstone Plateau – (all the high volcanic plateau), includes Washburn range
- (SR) Snake River plain

The snow samples (tables 2 and 5) are subdivided below into three regions:

- (MR) Madison Range (Beehive basin)
- (AR) Absaroka-Beartooth Mountains (most near Beartooth Pass)
- (YP) Washburn Range (Mt Washburn, and Yellowstone Plateau)

Finally, the thermal waters are classified (tables 3 and 6) into sites within and outside Yellowstone National Park

- Sites inside YNP (Norris, Norris-Mammoth corridor, Mammoth, Calcite, Rainbow, Washburn)
- Sites outside YNP (Corwin Springs KGRA; Northern Absarokas – Chico HS, Madison Range – Wolf Cr. HS)

Chemical Composition of Cold Water and Snow

The specific conductance values for snow samples, as expected for such a pristine setting are low, ranging from 2 to 12 $\mu\text{S}/\text{cm}$ (table 5). Only the concentrations of anions, other than bicarbonate, were determined for 4 snow samples, but these indicate that the higher conductance values probably result from dissolution of entrained carbonate minerals (Green and others, 2000).

The specific conductance values for most cold water samples are generally $<500 \mu\text{S}/\text{cm}$, and for many samples are $<100 \mu\text{S}/\text{cm}$ (table 4). Such values are typical for uncontaminated springs with shallow circulation paths and shallow ground water (Hem, 1985). A few cold-water samples, however, have specific conductance values greater than $1000 \mu\text{S}/\text{cm}$, with a maximum of $5200 \mu\text{S}/\text{cm}$. The samples with higher specific conductance indicate evaporative concentration of solutes and/or significant water-rock interaction in deeper circulation paths.

The chemical composition of water is highly variable reflecting the changes in local and regional geology (fig. 7). In general Ca, Mg and Na are the major cations and HCO_3 and SO_4 are the major anions (table 4). Concentrations of SiO_2 are relatively high, but those of Cl and K are relatively low. Alkalinity values were determined only for a limited number of samples, because the methodology is time consuming and requires field determination. Based on these limited determinations, mass balance of cations and anions (assuming equivalent HCO_3 for the excess cations) and the high Ca and Mg values, we conclude that HCO_3 , mainly from dissolution of carbonate minerals, comprises the bulk of anions.

Isotope Composition of Cold Water and Snow

The δD and $\delta^{18}\text{O}$ values for the 173 cold-water samples range from -115 to -153 and -15.2 to -20.2‰ , respectively. The δD and $\delta^{18}\text{O}$ values for the 40 snow samples, as expected, are generally lighter, ranging from -88 to -178 and -12.5 to -23.6‰ , respectively. The isotopic composition of snow varies greatly based on the snow events, thaw and freeze cycles, sublimation and evaporation and other complicating factors (Cooper, 1998), but the least-squares line for the snow samples (fig. 9) establishes a well constrained local meteoric water line (LMWL) given by $\delta\text{D} = 8.2 \delta^{18}\text{O} + 14.7$ ($r^2 = 0.99$). This line is close to the Global Meteoric Water Line (GMWL) given by $\delta\text{D} = 8\delta^{18}\text{O} + 10$ (Craig, 1961).

A large number of the δD and $\delta^{18}\text{O}$ values for cold-water samples plot on or close to the GMWL or the LMWL established by the isotope values for the snow samples (fig. 10). The δ values above the LMWL do not depart significantly from the line, whereas below the LMWL the δ values show a progressive shift away from the line with heavier δ values. The least squares line for the water samples gives the relationship $\delta\text{D} = 6.7 \delta^{18}\text{O} - 16.7$ ($r^2 = 0.90$). About 70% of the values fall within 2σ of the LMWL established using the snow data. However, the obvious progressive shift off the LMWL with increasing δ values and the overall slope of 6.7 strongly suggest that systematic evaporation is a major factor modifying the water isotopes (Thordsen and others, 1992).

Evaporation occurs mainly as rain droplets evaporate during descent from the cloud base through unsaturated air (Moser and Stichler, 1971) or during water percolation in the unsaturated rock. The d -parameter (Dansgaard, 1964), given by: $d = \delta\text{D} - 8\delta^{18}\text{O}$, is used to characterize the δD excess resulting from evaporation effects. A d -parameter value of 10‰ indicates that the water has not been significantly evaporated as it plots on the GMWL and close to LMWL; evaporated water has progressively lower d -parameter values and plots to the right of LMWL, with a variable slope (generally 3-5) that is a strong function of relative humidity, but also depends on temperature and wind speed. About 85% of the δ values that show the larger shifts from the LMWL have d -parameter values $<5\text{‰}$, and are from low altitude samples (<2100 m) that typically were collected in the rain shadow of high mountains (fig. 11).

The relationship between the d -parameter and altitude (fig. 11) and d -parameter or altitude versus specific conductance or sulfate concentration (figs. 12 and 13) although empirical, suggests that the evaporation trend is in large part caused by the "pseudo-altitude effect," whereby rainfall is enriched in heavy isotopes as droplets evaporate during descent from the cloud base through unsaturated air as well as water evaporation, especially while percolating in the unsaturated rock (Moser and Stichler, 1971; Clark and Fritz, 1997). According to Despain (1987), low altitude areas in the Yellowstone region receive proportionally more annual rainfall than snowfall relative to high altitude areas. The δD and $\delta^{18}\text{O}$ values for cold-water samples from the nine regions indicate that some areas (e.g., AN, Absaraka Range, north)

show the larger shifts from the LMWL, but the values in other areas (e.g., AR, Absaroka Range, northeast) plot close to the LMWL (fig. 14).

The spatial distribution of d -parameter (Dansgaard, 1964) is shown in figure 15, using the same grid and contouring methodology described below for the δD and $\delta^{18}O$ values for meteoric water samples depicted in figures 16 and 17. The d -parameter values $< 5\%$ indicating significant evaporation are located at lower altitudes (< 2100 m) and rain shadow of high mountains. Values of d -parameter greater than 10% appear in areas of high precipitation (figs. 8 and 15) in orographic regions and may be explained by precipitation in air with relative humidity close to 100% (Clark and Fritz, 1997).

The spatial distribution of the δD and $\delta^{18}O$ values for cold-water samples are shown in figures 16 and 17, respectively. Delta values are gridded and contoured using Arcview (version 3.2a) and Arcview Spatial Analyst module (ESRI), to 0.5 km grid cells, using an inverse distance weighted (IDW) function for 12 nearest neighbors. Delta values for all of the 136 cold-water sample sites are used to generate these contour plots; however for the sample sites (15 sites) that have two or more isotope samples, the lightest delta values are used. For δD distribution (fig. 16) the contour interval was selected to highlight the regions that contain δD values lighter than -149% , the δD values hypothesized by Truesdell and others (1977), for deep cold water recharge to the major hydrothermal basins in the Yellowstone Park; similarly for $\delta^{18}O$ distribution, the contour intervals highlight values lighter than $\sim -20\%$ (fig. 17).

The regional spatial distribution of $\delta^{18}O$ and δD values (figs. 16 and 17) shows a roughly circular pattern: isotopically lighter waters ($\delta^{18}O < -19.0\%$) are centered in the northern part of the Park and extend northwest along the Yellowstone River valley. Notwithstanding the "altitude effect" and other isotopic controls discussed below, the regional pattern appears to reflect the input of precipitation from air masses originating in the North Pacific and moving eastward, and also from cold Arctic air masses moving southward along the Yellowstone River valley. The extent of influence from northbound air masses from the Gulf of Mexico is difficult to interpret because of the sparse distribution of sample sites to the south and southeast of the Park.

The mountainous areas in the northern part of the Park are the likely locations of recharge water (see Origin and Evolution of Thermal Fluids below) for the hydrothermal fluids in Yellowstone. They are the only areas in the region with sufficiently light δD and $\delta^{18}O$ values to match the δD composition of the deep geothermal fluids calculated by Truesdell and others (1977).

Controls on Cold Water Isotopes

The temperature effect due to altitude apparently is the most important control on the distribution of water isotopes throughout the Yellowstone region. A plot of $\delta^{18}O$ values versus altitude for all the samples, however, indicates a complex relationship as it shows major departures from the expected lighter values with increasing altitude (fig. 18). On the other hand, the altitude relationship is well illustrated in figure 19, on which are plotted d -parameter, $\delta^{18}O$ and altitude for water samples located as a function of distance along a SW-to-NE traverse through the region (line A-A', fig. 15). Along the traverse from the Snake River plain to the crest of the Gallatin Range, the altitude gradually increases from 1700 to 2700 m over a distance of ~ 100 km, and the $\delta^{18}O$ values exhibit a nearly linear decrease from -17 to -20% (i.e. -3.0% per km increase in altitude). Water samples from the Absaroka Range (fig. 19), also exhibit a $\delta^{18}O$ correlation with altitude of about -3.5% per km increase in altitude, although the sampling distribution is sparse and limited to altitudes ranging from 1100 to 1800 m.

Water samples in the Yellowstone River valley, which separates the Gallatin and Absaroka Ranges, were collected at altitudes ranging from ~ 2700 m near the crest of the Gallatins to ~ 1500 m near the valley floor, but the $\delta^{18}O$ values mostly remain between -19 and -20% (fig. 19). Here, the altitude effect is obscured by what we term the 'canyon' effect. The 'canyon' effect results because the isotopic values of precipitation are controlled primarily by temperatures at the cloud base where phase transformations

occur, and the temperatures (altitude) of the cloud base are not significantly affected by the narrow, deep canyons, but are controlled by the altitude of the adjoining mountains (Kharaka and others, 1991; Thordsen and others, 1992).

The $\delta^{18}\text{O}$ vs. altitude relations for all of the water samples are shown in figure 20. Superimposed on the plot are estimated winter and summer $\delta^{18}\text{O}$ -altitude relationships (solid lines) calculated using the Mammoth, Yellowstone Park, WY weather station (altitude = 1902 m) as a reference (Thordsen and others, 1992). The $\delta^{18}\text{O}$ values are calculated for winter and summer conditions using: 1) the global temperature $\delta^{18}\text{O}$ relationship: $\delta^{18}\text{O} = 0.695T - 13.6$, where T is the average annual temperature, in $^{\circ}\text{C}$ (Dansgaard, 1964); 2) the 30 year average (1941-1970) at Mammoth for January and June (-7.1 and 17.4°C , respectively); and 3) the local winter and summer lapse rates (-0.53 and $-0.97^{\circ}\text{C}/100$ m, respectively), based on climatic and SNOTEL stations in the region (Despain, 1987).

The observed $\delta^{18}\text{O}$ values correspond remarkably closely to winter conditions predicted from the temperature-altitude relationships (fig. 20). The sampled ground waters are almost certainly derived predominantly from winter precipitation, with very little influence from summer precipitation. This conclusion appears to be confirmed by isotopic values for 10 cold springs that were sampled in May and September of 1991. The δD and $\delta^{18}\text{O}$ values for samples from 8 of the springs are constant within analytical error ($\sim 2.0\text{‰}$ δD and $\sim 0.2\text{‰}$ $\delta^{18}\text{O}$); the remaining 2 samples have undergone considerable evaporation.

The latitude and distance (i.e. continental) effects on the isotopic distribution probably are relatively minor within the limits of the study area ($\sim 200 \times 250$ km). In addition, these effects may be further obscured because air masses arrive over the Park from almost all directions. However, it is likely that the strong altitude vs. $\delta^{18}\text{O}$ relationship along the Snake River Plain-to-Gallatin crest (fig. 19) is enhanced by the distance and latitude effects as North Pacific air masses "rainout" and become depleted in heavy isotopes as they proceed to the northeast over the Yellowstone Plateau and Gallatin Range (Thordsen and others, 1992).

Hydrothermal Fluid Discharges

The exceptional number of geysers and other hydrothermal features of YNP result from a favorable combination of climatic and geologic factors, including a huge magmatic heat source present at a relatively shallow depth beneath the 0.6 Ma Yellowstone caldera, abundant supplies of recharge water primarily from melting snow and frequent seismic activity that creates new fractures and reopens clogged channels for fluid flow (Fournier, 1989; Wicks and others, 1998; Ball and others, 1998; Kharaka and others, 2000). Thermal water discharges for YNP have been estimated by totaling the measured rates of individual springs or groups of springs (Allen and Day, 1935) or by using the more accurate river chloride inventory method applied to the four major rivers that drain the Park (Fournier and others, 1976; Norton and Friedman, 1985, 1991, 2000; Sorey and Colvard, 1997; Ingebritsen and others, 2001). Results show large seasonal and long-term variations, and yield very high total average discharges of $3\text{--}4 \text{ m}^3/\text{s}$ (Fournier, 1989; Kharaka and others, 2000).

Thermal fluids in the Norris-Mammoth corridor, where our investigations were concentrated, discharge from many springs and thermal areas inside YNP, including Norris Geyser Basin, Roaring Mountain, Clearwater Springs, Sheepeater Canyon Hot Spring, High Bridge Spring, Mammoth Hot Springs and Hot River (figs. 1 and 2). Total fluid discharges from these areas average $\sim 0.8 \text{ m}^3/\text{s}$, with high fluid discharges obtained from the Norris Geyser Basin and Mammoth Hot Springs system. Norris Geyser Basin, located outside the northwest rim of the 0.6 Ma caldera, contains the widest diversity of hydrothermal activity known in the Park, discharging about $150\text{--}250 \text{ L/s}$ of water, which attains boiling temperature at surface and 360°C at depth (Fournier and others, 1976; White and others, 1988; Kharaka and others, 2000).

The highest thermal water and gas discharges in the corridor are from Mammoth Hot Springs, where travertine-precipitating thermal water issues from ~100 hot springs scattered over a score of step-like travertine terraces, covering a large area, ~1 km wide and 4 km long (figs. 2 and 3). The surface temperatures of the springs ($< 73^{\circ}\text{C}$) and the calculated reservoir temperature ($\sim 100^{\circ}\text{C}$) are lower than those of boiling springs encountered at Norris. However, the total thermal-water discharges from the Mammoth system, estimated from long-term flow and chloride flux measurements and extensive application of chemical tracers, are very large averaging 500-600 L/s. The calculated total heat flux from the Mammoth system (220 MW) is comparable to that discharged from the Norris Geyser Basin (Kharaka and others, 1991; Sorey and Colvard, 1997).

The gas concentration in thermal water from the Mammoth system, dominantly CO_2 , is considerable at ~66 mM/L, and equilibrium gas pressures > 5 bar are calculated for samples from the Y-10 well (Kharaka and others, 1991). The total CO_2 flux from the Mammoth system amounts to 33-40 M/s. The addition of 17 mM/L of dissolved C, present mainly as HCO_3^- in water samples from the Y-10 well (Kharaka and others, 1991), results in 42-50 M/s calculated total C flux from the Mammoth system.

Extensive tracer tests in 1989-90, using organic and inorganic compounds injected into water in sinkholes, travertine terraces and the Gardner River, established the flow paths, the mixing of thermal and cold surface and ground waters and the hydraulic connections between the thermal features in the Mammoth area (Kharaka and others, 1991; Sorey and others, 1991; Spall and others, 1992). Extensive flow and chloride and sulfate flux measurements and monitoring also were carried out in 1987-95, especially at Hot River, the Gardner River below Hot River and the Mammoth outflow (Sorey and Colvard, 1997). Results show that, despite the visual prominence of the Mammoth terraces, approximately 90% of total thermal water discharging from the Mammoth system is obtained from springs and seeps along the banks of the Gardner River, with the bulk emerging at Hot River. Results also indicate a general decrease of ~15% in total thermal water discharge from ~600 L/s in 1987 to ~500 L/s in 1995 (fig. 21). The decrease in discharge for a longer record (1984-2001) calculated by Friedman and Norton (2002) for the Mammoth system, however, was only 5%. The long-term decrease in discharge is probably related to decreases in regional precipitation rather than to tectonic or anthropogenic factors (Sorey and Colvard, 1997; Kharaka et al., 2000).

Thermal Water and Gas Compositions

The pristine hydrothermal waters (not modified by boiling and dilution) at the Norris Basin and Clearwater Springs are sinter-precipitating Na-K-Cl type waters (salinity 1,000-2,000 mg/L), high in SiO_2 , Li and B, and commonly modified by boiling, silica precipitation and mixing with local meteoric water (fig. 2). The thermal waters from Sheepeater Spring and northward in the corridor are markedly different, being travertine-precipitating Ca-Na-Mg- HCO_3 - SO_4 -Cl types, with higher salinities (2,000-3,000 mg/L) in the Mammoth Springs (table 6). Chemical geothermometry and $\delta^{34}\text{S}$ values (21‰) indicate that the high Ca, Mg and SO_4 are obtained from reaction with Paleozoic carbonates at $\sim 100^{\circ}\text{C}$. There are differences in the salinity and chemical composition of water among the terrace springs and other sites (e.g., Hot River) in the Mammoth system, but these changes result primarily from dilution with local meteoric water and travertine deposition (Kharaka and others, 1991).

In the Norris-Mammoth corridor, CO_2 is the dominant gas, comprising 96% to $> 99\%$ of the total, with locally significant H_2S and N_2 . In the Mammoth area, gas discharges are high and there are > 50 mM/L of excess CO_2 relative to Ca and Mg, indicating a source not related to dissolution of carbonates. The chemical and isotopic compositions of noble gases, especially the $^3\text{He}/^4\text{He}$ ratios, indicate a mantle origin for the excess CO_2 . The molar total $\text{C}/^3\text{He}$ ($\sim 5 \times 10^9$) and $\delta^{13}\text{C}$ values of CO_2 (-3.4 to -5.2%) are additional support for the conclusion of a mantle origin for the bulk of the CO_2 in the Mammoth system (Kennedy and others, 1985; Kharaka and others, 1991; Trull and others, 1993).

Origin and Evolution of Thermal Fluids

The δD and $\delta^{18}O$ values of waters, especially when combined with the concentrations of conservative solutes (for example Cl) are the best geochemical indicators of the origins, recharge locations, and flow paths of subsurface waters (for review articles and many references, see Truesdell and Hulston, 1980; Kharaka and Thordsen, 1992). The stable isotopes of water are useful tools because the relations governing their distribution in present-day surface and shallow ground waters of an area (the local meteoric water) as well as their modifications in aquifers are reasonably well known. In aquifers, the isotopes of meteoric water may be modified by evaporation and mixing at low temperatures and by mixing, boiling, and isotopic exchange with minerals at high temperatures.

The δD and $\delta^{18}O$ values of water from 37 thermal springs (total = 58 samples) are listed in table 6 and plotted in figure 22. Many of these samples were not included in Kharaka and others (1991), because they are either located outside the Norris-Mammoth corridor or they represent acid sulfate waters (fig. 22) that were sampled mainly for their gas compositions (Kharaka and others, 1992). Results of δD and $\delta^{18}O$ values shown in table 6 for several samples, including La Duke Hot Spring, Bear Creek-1, the Y-10 well, Narrow Gauge, Opal Terrace and Clearwater-3C are averages of two to four samples collected during 1989-1990 (fig. 2). For these sites, results of replicate sampling are constant within analytical errors of about $\pm 2\text{‰}$ for δD and $\pm 0.2\text{‰}$ for $\delta^{18}O$ values.

The δD and $\delta^{18}O$ values for selected thermal waters from Yellowstone National Park show significant δD and $\delta^{18}O$ shifts relative to the meteoric water line (fig. 22). The origins of isotopic shifts are complex and likely are different for each area of the Park. Truesdell and others (1977) discussed in detail the isotopic shifts resulting from single-stage or continuous boiling, isotopic exchange between water, dissolved SO_4 and geologic materials and mixing between thermal water and shallow cold meteoric water. Although increases in Cl concentrations are similar in single-stage or continuous steam separation, the H isotopic changes differ significantly. Because Cl behaves conservatively in geothermal systems, and water and steam are the only significant sources of H and D, Cl and SO_4 concentrations coupled with H isotopes of water can be useful interpretive tools (Truesdell and others, 1977; Fournier, 1989; Kharaka and others, 1991).

Kharaka and others (1991) showed that the isotopic shifts for the waters from Norris Geyser Basin relative to recharge waters with δD and $\delta^{18}O$ values of about -150‰ and -20‰ , respectively, result mainly from boiling for the δD values and from boiling and isotopic exchange with aquifer minerals for the $\delta^{18}O$ values. In addition to boiling, the isotopes of water from Clearwater Springs are modified by mixing with dilute local meteoric water with a δD value of about -144‰ ; this mixing is indicated by examination of the Cl vs. δD relations of the waters. The samples from Mammoth Hot Springs also show moderate isotopic shifts from the meteoric water line (Kharaka and others, 1991, table F-2 and fig. F-5). The three sites shown in figure F-5 (Narrow Gauge, Opal Terrace and the Y-10 well) were selected because the δD and $\delta^{18}O$ values of their waters remained constant for the duration of the study. The sample from the Y-10 well likely is the least modified of the three sites and the most representative of the upflow thermal water for the Mammoth system. This conclusion is reached because the water in the Y-10 well is at high pressure (~ 4 bars at ground level), is not affected by precipitation of travertine, and water isotope values are the same for water obtained at ground level and by downhole sampler from a depth of 53 m. The δD value of water from the Y-10 well (-149‰) is close to a δD value of -151‰ estimated for the recharge waters for the Mammoth system from the Cl vs. δD relations of thermal waters. The corresponding $\delta^{18}O$ value for the recharge waters is -20.1‰ , which would result in a moderate 1.7‰ shift in the $\delta^{18}O$ value of water from the Y-10 well.

There are two possible explanations for the moderate $\delta^{18}O$ shifts for the waters from the Y-10 well and the other sites from Mammoth Hot Springs. The oxygen shift could be the result of isotopic exchange between water and aquifer minerals as the water flows from recharge points in the Gallatin Range to the discharge sites at Mammoth. Oxygen exchange with calcite in Paleozoic limestone resulting in heavier

oxygen isotopes in water is a possible explanation because isotopic exchange can take place between water and calcite at relatively low (25° to 100°C) temperatures (Clayton and others, 1966; Kharaka and Carothers, 1986; Plummer and others, 1990). Alternatively, the oxygen shift also could result from mixing of a Mammoth meteoric water with the deep and unmodified thermal water from Norris Geyser Basin. The minor δD shifts (from a δD value of about -150‰) can be explained by mixing, as in the case of oxygen isotopes, or they could result from minor evaporation of recharge water before it percolates deep into the subsurface. The isotopic shifts also could result from hydrogen exchange with clay minerals in the sedimentary section (Kharaka and Thordsen, 1992).

Using water isotopes of thermal and meteoric water, Craig and others (1956) were the first to conclude that deep-percolating meteoric water was the source of all the thermal water in the Yellowstone National Park, with no or minimal magmatic contribution. This conclusion was supported by subsequent detailed investigations combining water isotopes with enthalpies and chemical compositions of thermal water (e.g. Truesdell and others, 1977; Fournier, 1989; Kharaka and others, 1991). Model calculations by Truesdell and others (1977) indicated that the source meteoric water for Norris, Lower and Shoshone Geyser basins and possibly for all of the other basins in Yellowstone Park has a well constrained δD value of -149‰ and an equivalent $\delta^{18}O$ value of -19.9‰.

The isotopic composition of present day precipitation (meteoric water) within and close to the geyser basins in the Park reported in this study and by Truesdell and others (1977), Kharaka and others (1991), Rye and Truesdell (1993) and others are generally heavier than that calculated for the recharge water of the hydrothermal system (Truesdell and others, 1977). The spatial distribution of cold-water samples shows a roughly circular pattern with isotopically lightest waters centered on the mountains and high plateau in the northwest corner of YNP, including the Yellowstone River valley, and becoming heavier in all directions; relatively light water isotopes are also present at high elevations in the southern Absaroka Range, but isotope data for this area are sparse (figs. 16 and 17). Results from this study show that meteoric water with δD and $\delta^{18}O$ values lighter than -149‰ and -19.9‰, respectively are present in the Gallatin and northern Absaroka Ranges at 2.5-3.0 km elevations and higher, and in the Yellowstone River valley at elevations of 1500 m and higher. The total land area, shown in figures 16 and 17, with δD and $\delta^{18}O$ values lighter than -149‰ and -19.9‰, respectively, is relatively small (~200 km²), and when combined with values for mean annual precipitation (~100 cm/yr, fig. 8) and a reasonable value (5-30%) for the recharged portion of precipitation (Sanford, 2002), yields a volume of this recharge water that is not adequate to supply the high total thermal water discharges (3-4 m³/s) from YNP.

The total land area located in the Gallatin and northern Absaroka Ranges (figs. 16 and 17) with δD values lighter than -145‰ is about 10,000 km², and precipitation over this area may be adequate for recharging the hydrothermal system in YNP. The value of -149‰ for the δD of recharge water, based on model calculations by Truesdell and others (1977) is generally accepted (e.g., Kharaka and others, 1991). Careful examination of data from Truesdell and others (1977), especially their critical data in figure 8, however could allow for a heavier δD value for the unmodified hydrothermal water, and thus for the recharged meteoric water. Fournier (1989) points out that the bottom hole temperature for the Y-12 well likely was 270°C rather than the 238°C used by Truesdell and others (1977), and the Cl concentration in the deep 360°C water was higher than the 310 mg/L used. Because hydrogen isotopic fractionation between water and steam results in the enrichment of steam with the heavy δD values at temperatures higher than 221°C (Giggenbach, 1992), the calculated δD value for the unmodified water from the Norris Geyser basin could be 2-4‰ heavier than the -149‰ value calculated by Truesdell and others (1977).

If a δD value lighter than -145‰ is required for the recharge water, it is possible that the hydrothermal water currently discharging from YNP was recharged during an earlier time when the mean annual temperatures were lower. In northern latitudes the δD values become lighter by 5.6‰ per °C decline in the mean annual temperature (Dansgard, 1964), and a modest lowering of only 0.7°C will change the δD values of precipitation from current values of $\geq -145‰$ to the required values of $\geq -149‰$. Climate records for the northern latitudes show significant temperature fluctuations with time (e.g., 1-2°C

lowering during the Little Ice Age) following the Pleistocene, and temperature changes of 5-10°C are indicated in the last 2 M yrs (Bryant, 1997). It is also possible that the hydrothermal water currently discharging from YNP represents a mixture of meteoric water having relatively heavy isotopes similar to present day precipitation with older meteoric water recharged during cooler periods, including during the Pleistocene when the δD values likely were 30-50‰ lighter than current values. A mixture comprised of about 90% water having present-day isotope values with 10% Pleistocene precipitation would be adequate as the source for the hydrothermal water currently discharging from YNP.

A Pleistocene age for even a small portion of the source meteoric water recharging the present hydrothermal system in YNP is probably unlikely, because the high discharge rates (3-4 m³/s) indicate a relatively short residence time. Radium and radon concentrations in thermal water also indicate that recharge water percolates rapidly (residence time ~500-1000 yrs) in the Norris-Mammoth corridor to the heat source at the Norris Geyser basin (Clark and Turekian, 1990). Model calculations using tritium values in thermal water from many geyser basins also yield low (200-1000 yrs) residence time for the recharge water (Pearson and Truesdell, 1978).

The most logical conclusion from the data discussed above is that the hydrothermal water presently discharging from YNP was recharged in the Gallatin and northern Absaroka Ranges during the Little Ice Age (1250-1900 AD). An acceptable interpretation of the isotope data for the hydrothermal water in YNP would allow the recharge meteoric water to have δD value lighter than -145‰, but keep the temperature and precipitation values in the region similar to their present day values.

Hydrothermal fluids from the Mammoth system

The pristine water from the Norris Basin has chemical, isotopic and thermal properties similar to those of waters from the caldera basins, which receive their heat and some chemical components from reaction with a relatively shallow magmatic source. The ³He/⁴He ratios relative to atmospheric values (R/Ra) yield high values (up to 9 at Norris and 16 inside the caldera), indicating that the magmatic He, CO₂ and other volatiles have a "deep" mantle origin (Kennedy and others, 1985; Hearn and others, 1990; Kharaka and others, 1992). The chemical and isotopic compositions of water and solutes, especially the ³He/⁴He ratios, in the Mammoth Springs indicate that water also derives its heat and some solutes (e.g., Cl, B, ³He and CO₂) from a magmatic source (Kharaka and others, 1991). White and others (1988) postulated that the magmatic source for Norris and the entire Norris-Mammoth corridor is located beneath Roaring Mountain. In this model, the lower concentrations of Cl, Br, B and other conservative solutes in the Mammoth water result from mixing 30-40% Norris-type water with 70-60% meteoric water as fluids flow northward to Mammoth; the much higher values for Ca, Mg, SO₄ and HCO₃ in the Mammoth water are obtained from reaction with Paleozoic carbonates at ~100°C (e.g., Kharaka and others, 2000).

Kharaka and others (1991) presented an alternative model and postulated that the heat and volatiles for the Mammoth system are provided by a separate magmatic body emplaced near Mammoth ~400 ka. A separate magmatic body is postulated, because (1) gas samples from the Y-10 well and three terrace springs yield R/Ra values of 8.1-8.4, and the sample from Snow Pass gives R/Ra value of 7.5, (2) all the major thermal areas between Norris and Mammoth, including Roaring Mountain, White Rock Springs, Amphitheater Springs, Clearwater Springs, and Horseshoe Hill, have lower R/Ra values of 2-3 (fig. 23). The emplacement of the magmatic system is constrained by model U/Th ages obtained from the extensive travertine deposits in the Mammoth area that indicate five periods of intermittent, but non-overlapping travertine precipitation from about 400 ka to present. The periods of activity could be related to the thickness of glacial ice in the region and/or magmatic injection at depth (Pierce and others, 1991). The ⁸⁷Sr/⁸⁶Sr ratios and ϵNd values of most travertines from the Mammoth system are identical, indicating precipitation from thermal fluids derived from the same hydrothermal system (Bullen and Kharaka, 1992). The exact location of the postulated Mammoth magmatic system is not known, but magnetotelluric

and other geophysical surveys conducted indicate partial melt conditions (500-600°C) occur south of Bunsen Peak at depths ≥ 6 km (Stanley and others, 1991). Additional evidence for a separate thermal source for the Mammoth system is obtained from satellite radar interferometry imaging for August 24, 2000 to September 13, 2001, that shows areas of significant inflation and surface uplift between the Norris Geyser Basin and Mammoth Springs that are separated from that imaged for the Norris Geyser Basin (W. C. Wicks, written communication, April, 25, 2002).

CONCLUSIONS

The δD and $\delta^{18}O$ values from snow cores establish a local meteoric water line nearly identical to the GMWL. For cold water samples, δD and $\delta^{18}O$ values plot near the GWML, although many δ values show a progressive shift away from the line with heavier δ values, probably caused by evaporation. The regional distribution of δ values shows a roughly circular pattern with the isotopically lightest waters occurring in the northern part of the Park and extending northward along the Yellowstone River valley.

Overall, the altitude effect appears to be the most important control on the distribution of isotopes. This effect is particularly well defined along a SW-NE traverse ascending the Snake River Plain to the crest of the Gallatin Range. However, on a regional scale the altitude effect is obscured because of several factors, including topographic complexities (i.e. deep canyons and rain shadows) and complex weather patterns.

Spring-water isotopic values are consistent with the major source of ground water originating from cold isotopically light winter precipitation. Seasonal variations are observed, but are difficult to quantify owing to sporadic sampling. Latitude and distance effects are minor within the confines of the study area.

The δD and $\delta^{18}O$ values for the extensive thermal-water discharges from Yellowstone National Park show significant δD and $\delta^{18}O$ shifts relative to the LMWL, but the origins of these isotopic shifts are complex and likely are different for each area of the Park. Isotopic shifts may result from single-stage or continuous boiling, isotopic exchange between water, dissolved SO_4 and geologic materials and mixing between thermal water and shallow cold meteoric water. The isotope values for cold water from elevations above about 2.5-3.0 km in the Gallatin and northern Absaroka Ranges (δD and $\delta^{18}O$ values lighter than -149‰ and -19.9‰ , respectively) are light enough that such water could be the presumed recharge water for the hydrothermal system in the Park (Truesdell and others, 1977).

Estimations of the volume of present-day recharged water that is isotopically light, indicate that it is not adequate to supply the huge thermal water discharges from YNP. The most logical conclusion from all the chemical and isotope data is that the hydrothermal water presently discharging from YNP was recharged in the Gallatin and northern Absaroka Ranges during the Little Ice Age (1250-1900 AD), when the mean annual temperatures likely were lower by 1-2°C (Bryant, 1997). An alternative interpretation of the isotope data for the hydrothermal water in YNP would allow the recharge meteoric water to have δD value lighter than -145‰ , but keep the temperature and precipitation values in the region similar to their present day values. Detailed investigation of recharge in the region is an important future research topic.

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Table 1. Site name and location of cold springs and wells in and adjacent to Yellowstone National Park
[Water type - cs, cold spring; ms, cold mineral spring; cw, cold well; n, number of samples
Altitude, in meters above mean sea level]

Site name	Local site name	Water type	n	Latitude	Longitude	Altitude
(AN) - Absaroka Range - northern area						
AN-1	Unn. spr.	cs	1	45° 19' 56"	110° 41' 25"	1682
AN-2	Unn. spr.	cs	1	45° 29' 45"	110° 31' 13"	1719
AN-3	well	cw	1	45° 44' 9"	110° 12' 40"	1323
AN-4	well	cw	1	45° 32' 51"	110° 18' 26"	1689
AN-5	Unn. spr.	cs	1	45° 33' 4"	110° 3' 23"	1811
AN-6	Unn. spr.	cs	1	45° 40' 29"	109° 36' 5"	1326
AN-7	Unn. spr.	cs	1	45° 34' 57"	109° 41' 46"	1559
AN-8	Unn. spr.	cs	1	45° 34' 11"	109° 48' 36"	1673
AN-9	Unn. spr.	cs	1	45° 35' 54"	109° 46' 32"	1494
AN-10	Unn. spr.	cs	1	45° 22' 42"	109° 39' 30"	1642
AN-11	Unn. spr.	cs	1	45° 40' 11"	109° 16' 59"	1141
AN-12	Unn. spr.	cs	1	45° 28' 11"	109° 54' 50"	1829
AN-13	well	cs	1	45° 21' 12"	109° 53' 51"	1579
AN-14	well	cw	1	45° 40' 15"	109° 16' 54"	1131
AN-M	Montanapolis Spring	ms	3	45° 17' 28"	110° 31' 9"	1841
(AR) Absaroka Range - northeast of YNP, between northeast gate and Red Lodge, MT						
AR-1	Unn. spr.	cs	1	45° 9' 23"	109° 22' 27"	2067
AR-2	well	cw	1	45° 10' 23"	109° 27' 0"	2298
AR-3	well	cw	1	45° 3' 29"	109° 24' 42"	2195
AR-4	Unn. spr.	cs	4	45° 1' 35.2"	109° 53' 36.1"	2451
AR-5	well	cw	1	45° 1' 27"	109° 54' 42"	2377
AR-6	Unn. spr.	cs	1	44° 55' 37.7"	109° 32' 8.7"	2987
AR-7	Unn. spr.	cs	1	44° 58' 9.2"	109° 28' 55.3"	3249
AR-8	Unn. spr.	cs	1	44° 57' 50.2"	109° 28' 44.7"	3191
AR-9	Unn. spr.	cs	1	44° 57' 53.7"	109° 28' 44.7"	3191
AR-10	Unn. spr.	cs	1	44° 59' 53.7"	109° 25' 13.4"	3170
AR-11	Unn. spr.	cs	1	44° 58' 37.7"	109° 26' 54.9"	3200
AR-12	well	cw	1	44° 56' 47"	109° 35' 9.4"	2719
AR-13	well	cw	1	45° 0' 27.7"	109° 59' 22.6"	2217
(AC) Absaroka Range - east of YNP eastgate, between east gate and Cody, WY						
AC-1	Unn. spr.	cs	1	44° 36' 43"	109° 7' 54"	1713
AC-2	well	cw	1	44° 27' 56"	109° 37' 18"	1807
AC-3	Newton Spring	cs	1	44° 27' 22"	109° 45' 16"	1926
AC-4	Unn. spr.	cs	1	44° 29' 59"	109° 55' 50"	2079
(AD) Absaroka Range - southern area, near Dubois WY						
AD-1	Unn. spr.	cs	1	43° 43' 10"	109° 58' 31"	2585
AD-2	well	cw	1	43° 42' 17"	109° 58' 5"	2548
AD-3	Unn. spr.	cs	1	43° 36' 15"	109° 57' 19"	2761
AD-4	Unn. spr.	cs	1	43° 34' 5"	109° 52' 59"	2640
AD-5	Unn. spr.	cs	1	43° 30' 28"	109° 50' 38"	2960
AD-6	well	cw	1	43° 40' 18"	109° 38' 27"	2377
AD-7	Bartrand Spring	cs	1	43° 41' 59"	109° 36' 41"	2499
AD-8	Unn. spr.	cs	1	43° 40' 1"	109° 38' 5"	2341
AD-9	Unn. spr.	cs	1	43° 42' 2"	109° 41' 41"	2865

Table 1. Site name and location of cold springs and wells in and adjacent to YNP - continued

Site name	Local site name	Water type	n	Latitude	Longitude	Altitude
AD-10	Unn. spr.	cs	1	43° 41' 5"	109° 45' 47"	2548
AD-11	Unn. spr.	cs	1	43° 41' 5"	109° 45' 47"	2548
AD-12	Unn. spr.	cs	1	43° 41' 6"	109° 22' 18"	2566
AD-13	Unn. spr.	cs	1	43° 41' 51"	109° 26' 3"	2804
AD-14	well	cw	1	43° 38' 45"	109° 29' 57"	2256
(AG) Absaroka Range - Gardiner-Mammoth area						
AG-1	well (CUT)	cw	2	45° 5' 20.5"	110° 46' 36.2"	1579
AG-2	well	cw	1	45° 3' 10.4"	110° 42' 7.9"	1899
AG-3	well	cw	1	45° 2' 4.6"	110° 41' 8.7"	1713
AG-4	Unn. spr.	cs	1	45° 2' 14.4"	110° 41' 56.9"	1682
AG-5	Unn. spr.	cs	3	45° 3' 9.6"	110° 35' 9.3"	2633
AG-6	Unn. spr.	cs	2	45° 4' 11"	110° 38' 38"	2073
AG-7	Unn. spr.	cs	1	45° 2' 43"	110° 35' 40"	2646
AG-8	Unn. spr.	cs	1	45° 2' 35"	110° 35' 55"	2560
AG-9	Unn. spr.	cs	3	45° 3' 33"	110° 37' 58"	2073
AG-10	Unn. spr.	cs	3	45° 2' 8.9"	110° 40' 39.7"	1792
AG-11	Unn. spr.	cs	3	45° 5' 54"	110° 46' 22"	1804
AG-12	Unn. spr.	cs	1	45° 7' 15.3"	110° 44' 34.4"	2243
AG-13	Unn. spr.	cs	1	45° 7' 47.8"	110° 44' 47.2"	2499
AG-14	well	cs	1	45° 4' 58"	110° 46' 34.7"	1573
AG-15	well (Hoppe)	cw	1	45° 2' 4.2"	110° 40' 49.6"	1783
(YP) Yellowstone Plateau - including interior volcanic plateaus, and Washburn Range						
YP-1	Unn. spr.	cs	3	44° 42' 29"	111° 5' 57"	2012
YP-2	well	cw	1	44° 56' 54"	110° 18' 29"	1905
YP-3	Unn. spr.	cs	5	44° 53' 20.7"	110° 23' 24"	2009
YP-4	Unn. spr.	cs	2	44° 32' 8"	110° 26' 12"	2362
YP-5	Iron Spring	cs	1	44° 39' 36"	110° 46' 7"	2176
YP-6	Unn. spr.	cs	4	44° 38' 14.5"	110° 51' 45.4"	2051
YP-7	well	cw	1	44° 44' 23"	110° 41' 30"	2281
YP-8	well	cw	1	44° 16' 53"	110° 37' 36"	2380
YP-9	well	cw	1	44° 55' 2"	110° 6' 45"	2104
(GG) Gallatin Range - Gardiner-Mammoth area						
GG-1	Unn. spr.	cs	4	44° 59' 18.8"	110° 42' 58.9"	2035
GG-2	well (NPS-1)	cw	1	45° 3' 15.3"	110° 45' 54.9"	1579
GG-3	Unn. spr.	cs	1	44° 59' 5.6"	110° 48' 55"	2512
GG-4	Unn. spr.	cs	1	44° 59' 7.4"	110° 48' 19.1"	2451
GG-5	Unn. spr.	cs	1	44° 58' 17.2"	110° 46' 13.5"	2390
GG-6	Unn. spr.	cs	1	44° 57' 40.6"	110° 44' 22.5"	2316
GG-7	Unn. spr.	cs	1	44° 56' 37"	110° 49' 51"	2505
GG-8	Unn. spr.	cs	1	44° 56' 58"	110° 46' 41"	2353
GG-9	Unn. spr.	cs	1	45° 3' 5.9"	110° 48' 12.1"	2505
GG-10	Unn. spr. (Sawmill Cr. Spr.)	cs	2	45° 2' 44"	110° 48' 11.4"	2036
GG-11	Unn. spr.	cs	1	45° 2' 7.7"	110° 46' 14.3"	1728
GG-12	Apollinaris Spring	cs	1	44° 50' 33"	110° 43' 54"	2243
GG-13	well	cw	1	44° 53' 9"	110° 44' 7"	2231
GG-14	Unn. spr.	cs	3	44° 59' 19.6"	110° 42' 58.9"	2035
GG-15	Unn. spr.	cs	1	44° 57' 31.6"	110° 43' 60"	2286

Table 1. Site name and location of cold springs and wells in and adjacent to YNP - continued

Site name	Local site name	Water type	n	Latitude	Longitude	Altitude
(GN) Gallatin Range - northern area						
GN-1	Unn. spr.	cs	1	45° 12' 57"	110° 56' 26"	1838
GN-2	Unn. spr.	cs	1	45° 14' 1"	110° 58' 9"	2140
GN-3	Unn. spr.	cs	1	45° 14' 1"	110° 58' 9"	2140
GN-4	Unn. spr.	cs	1	45° 14' 1"	110° 58' 9"	2140
GN-5	Unn. spr.	cs	1	45° 13' 49"	110° 57' 11"	2060
GN-6	Unn. spr.	cs	1	45° 3' 28"	110° 56' 20.2"	2682
GN-7	Unn. spr.	cs	1	45° 5' 23.2"	110° 58' 19"	2591
GN-8	Unn. spr.	cs	1	45° 3' 29"	110° 56' 17.3"	2682
GN-9	Unn. spr.	cs	1	45° 19' 3"	111° 10' 21"	1951
GN-10	well	cw	1	45° 22' 18"	111° 9' 9"	1774
GN-11	Unn. spr.	cs	1	45° 26' 24"	111° 11' 29"	1707
GN-12	Unn. spr.	cs	1	45° 25' 33"	111° 8' 21"	1835
GN-13	Unn. spr.	cs	1	45° 26' 11"	111° 10' 40"	1747
GN-14	Unn. spr.	cs	1	45° 31' 39"	111° 1' 8"	1914
GN-15	Unn. spr.	cs	1	45° 31' 25"	111° 1' 5"	1902
GN-16	Unn. spr.	cs	1	45° 38' 23"	110° 42' 24"	1588
(MR) Madison Range - northwest of YNP, including sites in south Gravelly Range						
MR-1	Unn. spr.	cs	1	45° 33' 3"	111° 26' 22"	1682
MR-2	Unn. spr.	cs	1	45° 29' 42"	111° 25' 13"	1811
MR-3	well	cw	1	45° 26' 50"	111° 22' 34"	1865
MR-4	well	cw	1	45° 36' 24.8"	111° 34' 10.9"	1366
MR-5	Unn. spr.	cs	1	45° 34' 45.1"	111° 40' 41.9"	1487
MR-6	Unn. spr.	cs	1	45° 27' 15.8"	111° 37' 18.1"	1823
MR-7	Unn. spr.	cs	1	45° 21' 5"	111° 24' 9"	2987
MR-8	Unn. spr.	cs	2	45° 20' 19"	111° 23' 49"	2761
MR-9	Unn. spr.	cs	1	45° 19' 37"	111° 23' 12"	2621
MR-10	Unn. spr.	cs	1	44° 53' 7"	111° 3' 11"	2164
MR-11	Unn. spr.	cs	1	44° 53' 52"	111° 3' 21"	2195
MR-12	Unn. spr.	cs	1	44° 49' 46.9"	111° 31' 4.1"	1850
MR-13	Unn. spr.	cs	1	44° 48' 14"	111° 33' 40"	1914
MR-14	Unn. spr.	cs	1	44° 48' 13"	111° 33' 32"	1914
MR-15	well	cw	1	44° 47' 49.9"	111° 33' 36"	2012
MR-16	Unn. spr.	cs	1	44° 46' 4.1"	111° 29' 53.2"	1963
MR-17	Unn. spr.	cs	1	45° 21' 6.5"	111° 24' 8.9"	3005
MR-18	Unn. spr.	cs	1	45° 21' 6.9"	111° 24' 5.2"	3011
MR-19	Unn. spr.	cs	1	45° 20' 47.2"	111° 23' 43.6"	2853
Snake River Plain - southwest of YNP						
SR-1	Unn. spr.	cs	1	44° 11' 28"	111° 33' 53"	1695
SR-2	Unn. spr.	cs	1	44° 13' 10"	111° 37' 51"	1792
SR-3	Elk Wallow well	cw	1	44° 13' 16"	111° 29' 37"	1901
SR-4	Unn. spr.	cs	1	44° 17' 4"	111° 30' 59"	1897
SR-5	North Antelope Spring	cs	1	44° 18' 36"	111° 36' 19"	2079
SR-6	Lyle Spring	cs	1	44° 18' 2"	111° 32' 40"	1957
SR-7	Osborne Springs	cs	1	44° 18' 32"	111° 24' 26"	1868
SR-8	Unn. spr.	cs	1	44° 17' 2"	111° 18' 54"	1870
SR-9	Unn. spr.	cs	1	44° 26' 19"	111° 15' 30"	1939

Table 1. Site name and location of cold springs and wells in and adjacent to YNP - continued

Site name	Local site name	Water type	n	Latitude	Longitude	Altitude
SR-10	Latham Spring	cs	1	44° 27' 34"	111° 8' 34"	2323
SR-11	Big Springs (southern)	cs	4	44° 29' 56"	111° 15' 14"	1951
SR-12	Big Springs (northern)	cs	3	44° 30' 2"	111° 15' 14"	1951
SR-13	Unn. spr.	cs	1	44° 32' 13"	111° 15' 27"	1957
SR-14	Unn. spr.	cs	1	44° 35' 35"	111° 16' 27"	2091
SR-15	Black Sand Spring	cs	1	44° 39' 33"	111° 9' 35"	2018
SR-16	Howard Spring	cs	1	44° 40' 8"	111° 17' 10"	2140

Table 2. Site name and location for snow samples in and adjacent to Yellowstone National Park
[sfc, surface sample; n, number of samples; Altitude, in meters above mean sea level]

Site name	Local site name	Water type	n	Latitude	Longitude	Altitude
Absaroka Range - northeast of YNP, between northeast gate and Red Lodge, MT along Highway 212						
AR-S1	Beartooth Pass	sfc	1	45° 0' 28.2"	109° 24' 30"	3109
AR-S2	Beartooth Pass, nr ski resort	core	1	44° 58' 31"	109° 26' 0.6"	3328
AR-S3	Beartooth Pass, at saddle	core	1	44° 58' 27.7"	109° 27' 17"	3210
AR-S4	Beartooth Pass - West Summit rest area	core	2	44° 58' 10.9"	109° 28' 15.8"	3335
AR-S5	Beartooth Pass - snow 10300'	core	2	44° 57' 48.1"	109° 28' 55.6"	3164
AR-S6	near Long Lake	core	1	44° 56' 27"	109° 30' 21.8"	2943
AR-S7	Beartooth Lake campground	core	2	44° 56' 31.4"	109° 35' 44.7"	2720
AR-S8	Chief Joseph campground	core	2	45° 1' 7.8"	109° 52' 17.9"	2448
Yellowstone Plateau - including interior volcanic plateaus and Washburn Range						
YP-S1	Dunraven Pass	core	3	44° 47' 5.9"	110° 27' 10.6"	2697
YP-S2	Mt Washburn, near summit at 10220'	core	1	44° 47' 53"	110° 25' 59.2"	3115
YP-S3	Mt Washburn, north ridge at 9860'	core	2	44° 48' 4"	110° 26' 5.6"	3005
YP-S4	Mt Washburn, north ridge at 9620'	core	1	44° 48' 24.2"	110° 26' 1.1"	2932
YP-S5	Mt Washburn, north ridge at 9150'	core	1	44° 48' 49.2"	110° 26' 24.4"	2789
YP-S6	Mt Washburn, north ridge at 8820'	core	1	44° 49' 22.4"	110° 26' 39.4"	2688
YP-S7	Cascade Lake picnic area	core	1	44° 44' 32.7"	110° 29' 37.5"	2426
YP-S8	near Palmer Creek, near AG-5 cold spring	core	1	45° 3' 4.6"	110° 35' 9.3"	2633
YP-S9	Norris Basin, at parking lot	sfc	1	44° 43' 35.1"	110° 42' 2.3"	2312
YP-S10	Ice Lake Trail	sfc	1	44° 43' 0"	110° 38' 4.9"	2402
YP-S11	Canyon Junction	sfc	1	44° 44' 8.7"	110° 29' 32.3"	2409
YP-S12	Mt. Washburn, parking lot near summit	sfc	1	44° 49' 26"	110° 26' 41.1"	2667
YP-S13	Mt. Washburn, north road to summit	sfc	1	44° 50' 25.7"	110° 26' 16.1"	2499
YP-S14	Dunraven picnic area	sfc	1	44° 45' 45.4"	110° 28' 16.7"	2545
YP-S15	Continental Divide nr Grant Village	sfc	2	44° 21' 26.4"	110° 34' 53.9"	2437
Madison Range - Beehive basin, near Lone Mountain ski area, MT						
MR-S1	Beehive Basin @ 2621 m	core	1	45° 19' 37.3"	111° 23' 12.5"	2621
MR-S2	Beehive Basin @ 2682 m	core	1	45° 19' 39.3"	111° 23' 4.6"	2682
MR-S3	Beehive Basin, trailhead @ 2554 m	core	1	45° 18' 56.7"	111° 23' 3.2"	2554
MR-S4	Beehive Basin @ 2493 m	core	1	45° 18' 42.9"	111° 23' 2.2"	2493
MR-S5	Beehive Basin @ 2432 m	core	1	45° 18' 26.4"	111° 22' 56.2"	2432
MR-S6	Beehive Basin, 2m profile (0.5m intervals)	profile	4	45° 19' 25.5"	111° 23' 6.4"	2627

Table 3. Site name and location for thermal and mineral waters in and adjacent to Yellowstone National Park
[Water type - ts, thermal spring; tw, thermal well; n = number of samples;
Altitude, in meters above mean sea level]

Site name	Local site name	Water type	n	Latitude	Longitude	Altitude
<i>Sites inside Yellowstone National Park boundary</i>						
Mammoth Area						
M-NG	Narrow Gauge	ts	3	44° 58' 11.1"	110° 42' 32.2"	2012
M-OT	Opal Terrace	ts	1	44° 58' 23.4"	110° 42' 8.5"	1913
M-PP	Painted Pool	ts	1	44° 57' 55.3"	110° 42' 48.8"	2054
M-PS	Poison Spring	ts	1	44° 57' 53.4"	110° 42' 55.8"	2062
M-SP	Unn. spr. (Snow Pass)	ts	2	44° 57' 30.5"	110° 44' 7.8"	2274
M-Y10	well (Y-10)	tw	5	44° 57' 57.7"	110° 42' 47.3"	2055
Norris-Mammoth Corridor						
NM-AS1	Amphitheater Springs (#1)	ts	1	44° 47' 42.9"	110° 43' 26.9"	2301
NM-AS2	Amphitheater Springs (#2)	ts	1	44° 47' 48.9"	110° 43' 24.2"	2298
NM-CW1	Clearwater Springs (CW-1)	ts	1	44° 47' 9.3"	110° 44' 21.1"	2295
NM-CW2	Clearwater Springs (CW-2)	ts	1	44° 47' 17.5"	110° 44' 18.4"	2292
NM-CW3	Clearwater Springs (CW-3)	ts	4	44° 47' 20.2"	110° 44' 19.5"	2292
NM-HB	Unn. wm. spr. (High Bridge)	ts	1	44° 57' 0.3"	110° 40' 53.8"	1821
NM-S	Sheepeater Hot Springs	ts	2	44° 54' 31.9"	110° 42' 24"	2131
NW-W	Whiterock Springs	ts	1	44° 46' 47.8"	110° 41' 58.4"	2310
Norris Basin						
N-C	Cistern Spring	ts	1	44° 43' 23.1"	110° 42' 11.7"	2291
N-G	Growler	ts	1	44° 43' 48.2"	110° 41' 57.9"	2295
N-PG	Porkchop Geyser	ts	2	44° 43' 20"	110° 42' 26.6"	2288
N-NP	Unn. acid spr. (nr. Porkchop Geyser)	ts	1	44° 43' 20.6"	110° 42' 26.6"	2287
Calcite Springs thermal Area (near Tower Junction)						
YP-C1	Unn. spr. (Calcite Spr.)	ts	3	44° 54' 18.9"	110° 23' 40.1"	1856
YP-C2	Unn. spr. (Calcite Spr.)	ts	1	44° 54' 22.8"	110° 23' 39"	1856
Rainbow Springs thermal area (Wrong Creek- southwest side of Mirror Plateau)						
YP-R2	Rainbow Springs (YRS-2)	ts	1	44° 46' 8.5"	110° 16' 11.1"	2490
YP-R33	Rainbow Springs (#33)	ts	1	44° 46' 8.5"	110° 16' 11.1"	2490
YP-R4	Rainbow Springs (#4)	ts	1	44° 46' 8.5"	110° 16' 11.1"	2490
YP-ROS	Rainbow Springs (oil seep)	ts	1	44° 46' 8.5"	110° 16' 11.1"	2490
Washburn Hot Springs thermal area (Washburn Range, east flank)						
YP-W1	Washburn Hot Springs (#1)	ts	1	44° 46' 0.6"	110° 25' 37.8"	2527
YP-W2	Washburn Hot Springs (#2)	ts	1	44° 45' 58.3"	110° 25' 44.3"	2512
<i>Thermal waters- Outside Yellowstone National Park</i>						
Corwin Springs Known Geothermal Resources Area						
CS-BC1	Bear Creek Hot Springs (BC-1)	ts	1	45° 1' 57.8"	110° 41' 1.8"	1634
CS-BC2	Bear Creek Hot Springs (BC-2)	ts	2	45° 1' 50.9"	110° 41' 1.5"	1622
CS-BC3	Bear Creek Hot Springs (BC-3)	ts	1	45° 1' 50.1"	110° 41' 15.9"	1609
CS-BCG	Bear Creek Hot Springs, at gauge	ts	1	45° 1' 54.6"	110° 41' 1.7"	1625
CS-LD	La Duke Hot Springs	ts	4	45° 5' 25.8"	110° 46' 27.9"	1567
CS-MS	Unn. spr., near Miller Well	ts	1	45° 4' 58"	110° 46' 36.2"	1564
CS-NL	Unn. spr. (near La Duke HS)	ts	1	45° 5' 13.3"	110° 46' 29"	1567
CS-MW	well (Miller)	tw	3	45° 4' 57.7"	110° 46' 35.6"	1564
CS-CUT1	well (CUT-1)	tw	1	45° 5' 21.1"	110° 46' 33.4"	1576

Table 3. Site name and location for thermal and mineral waters in and adjacent to YNP - continued

Site name	Local site name	Water type	n	Latitude	Longitude	Altitude
Absaroka Range - northern area						
AN-C	Chico Hot Springs	ts	2	45° 20' 12"	110° 41' 29.3"	1615
Madison Range						
MR-WC	Wolf Creek Hot Springs	ts	1	44° 59' 3"	111° 36' 54"	1850

Table 4.--Physical and chemical analyses of cold water samples from the greater Yellowstone National Park area

[Deg C, degrees Celsius; $\mu\text{S}/\text{cm}$, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; --, not determined; <, less than]

Site Name	Field Sample ID	Date	Temperature, water (Deg C)	Specific conductance (μS/cm)	pH (stand-ard units)	Silica, dissolved (mg/L as SiO ₂)	Calcium, dissolved (mg/L as Ca)	Magne-sium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potas-sium, dissolved (mg/L as K)	Alka-linity, lab (mg/L as HCO ₃)	Sulfate, dissolved (mg/L as SO ₄)	Chlo-ride, dissolved (mg/L as Cl)	Solids, sum of consti-tuents, dissolved (mg/L)
(AN) Absaroka Range - northern area														
AN-1	89YNP-212	06-24-89	8	166	--	17.5	23.3	3.81	5.7	0.79	--	3.2	1.1	56
AN-2	90YNP-224	06-06-90	4	139	--	12.8	16.3	4.63	2.2	--	--	9.6	0.9	48
AN-3	90YNP-226	06-06-90	11	252	--	10.3	5.49	0.15	53.8	0.06	--	39.4	3.9	114
AN-4	90YNP-227	06-06-90	11	410	--	7.0	56.8	12.2	10.8	--	--	73.3	0.5	162
AN-5	90YNP-228	06-06-90	6	495	--	10.1	75.0	16.9	6.6	--	--	15.7	2.6	130
AN-6	90YNP-229	06-07-90	8	630	--	6.3	59.3	26.8	43.3	2.10	--	63.9	2.7	207
AN-7	90YNP-230	06-07-90	10	380	--	6.7	43.3	15.1	16.1	--	--	11.7	1.5	97
AN-8	90YNP-231	06-07-90	7	240	--	19.6	37.3	4.06	6.7	--	--	7.8	0.7	77
AN-9	90YNP-232	06-07-90	--	--	--	--	--	--	--	--	--	--	--	--
AN-10	90YNP-235	06-07-90	12	620	--	8.8	70.0	26.9	8.0	--	--	16.8	2.5	139
AN-11	90YNP-236	06-07-90	9	970	--	8.5	36.0	16.4	177	2.12	--	107	9.1	358
AN-12	90YNP-233	06-08-90	8	670	--	11.4	97.2	28.4	6.2	--	--	173	0.9	319
AN-13	90YNP-234	06-08-90	8	65	--	10.6	6.43	1.72	2.1	--	--	4.8	0.3	27
AN-14	90YNP-237	06-08-90	10.5	890	--	8.3	21.7	11.9	180	1.84	--	69.6	11.3	307
AN-M.1	89YNP-213	06-24-89	9	5200	--	--	--	--	--	--	--	--	--	--
AN-M.2	90YNP-225	06-06-90	--	--	--	--	--	--	--	--	--	--	--	--
AN-M.3	90YNP-319	08-15-90	10	5200	--	23.8	393	87.5	968	60.9	2960	678	243	5434
(AR) Absaroka Range - northeast of YNP, between northeast gate and Red Lodge, MT														
AR-1	90YNP-238	06-09-90	6	66	--	8.9	6.27	2.66	1.5	--	--	3.0	0.3	23
AR-2	90YNP-239	06-09-90	3	100	--	8.2	9.37	4.88	2.4	--	--	2.6	0.2	29
AR-3	90YNP-240	06-09-90	5	130	--	9.2	14.1	6.06	1.9	--	--	5.9	0.4	39
AR-4.1	90YNP-246	06-11-90	2	105	--	10.9	14.8	3.65	1.0	--	--	3.1	0.4	35
AR-4.2	90YNP-318	08-14-90	5	130	--	12.8	17.2	4.21	1.7	--	--	3.0	0.3	40
AR-4.3	91YNP-8	05-26-91	--	106	--	10.7	14.6	3.45	1.4	0.41	--	3.0	0.4	35
AR-4.4	91YNP-116	09-02-91	3	121	--	--	--	--	--	--	--	2.8	0.3	--
AR-5	90YNP-247	06-11-90	8	265	--	8.9	42.7	8.32	0.9	--	--	8.4	0.8	73
AR-6	91YNP-109	09-02-91	4	17	--	--	--	--	--	--	--	0.68	0.4	--

Table 4. Physical and chemical analyses of cold water samples from the greater Yellowstone National Park area - continued
[mg/L, milligrams per liter; --, not determined; <, less than]

Site Name	Ammo- nium, dis- solved (mg/L as NH ₄)	Barium, dis- solved (mg/L as Ba)	Boron, dis- solved (mg/L as B)	Bromide, dis- solved (mg/L as Br)	Fluo- ride, dis- solved (mg/L as F)	Iron, dis- solved (mg/L as Fe)	Lithium, dis- solved (mg/L as Li)	Manga- nese, dis- solved (mg/L as Mn)	Nitrate, dis- solved (mg/L as NO ₃)	Phos- phate, dis- solved (mg/L as PO ₄)	Stron- tium, dis- solved (mg/L as Sr)	O-18/ O-16, stable isotope ratio (permil)	H-2/ H-1, stable isotope ratio (permil)	d-pa- ra- meter
(AN) Absaroka Range - northern area														
AN-1	--	0.040	<0.05	<0.03	0.08	<0.01	--	<0.002	<0.02	<0.05	0.172	-19.0	-140	11.9
AN-2	--	0.031	<0.05	<0.2	<0.1	0.01	--	<0.002	1.2	<0.30	0.029	-17.9	-136	7.2
AN-3	--	<0.002	<0.05	<0.2	0.34	0.01	--	<0.002	0.2	<0.30	0.019	-15.2	-122	-0.5
AN-4	--	0.093	<0.05	<0.2	0.12	<0.01	--	0.005	0.6	<0.30	0.169	-18.7	-141	8.4
AN-5	--	0.13	<0.05	<0.2	0.13	<0.01	--	<0.002	2.1	<0.30	0.349	-17.9	-137	5.5
AN-6	--	0.12	0.22	<0.2	0.28	<0.01	--	<0.002	1.0	<0.30	1.67	-17.5	-137	2.4
AN-7	--	0.13	0.11	<0.2	0.20	<0.01	--	<0.002	<0.1	<0.30	1.53	-16.7	-132	2.1
AN-8	--	<0.002	<0.05	<0.2	0.11	<0.01	--	<0.002	<0.1	<0.30	0.121	-17.5	-135	4.6
AN-9	--	--	--	--	--	--	--	--	--	--	--	-17.2	-131	6.8
AN-10	--	0.074	<0.05	<0.2	0.19	<0.01	--	0.003	4.51	<0.30	0.433	-16.7	-131	2.4
AN-11	--	0.052	0.37	<0.2	0.32	<0.01	--	<0.002	0.76	<0.30	1.13	-16.9	-135	-0.3
AN-12	--	0.026	<0.05	<0.2	0.19	<0.01	--	<0.002	<0.1	<0.30	1.42	-18.3	-139	7.1
AN-13	--	0.007	<0.05	<0.2	<0.1	0.02	--	0.032	0.39	<0.30	0.046	-18.7	-139	10.3
AN-14	--	0.20	0.54	<0.2	1.0	0.03	--	0.011	<0.1	<0.30	0.717	-17.1	-137	0.2
AN-M.1	--	--	--	--	--	--	--	--	--	--	--	-19.7	-150	7.6
AN-M.2	--	--	--	--	--	--	--	--	--	--	--	-19.6	-153	3.6
AN-M.3	--	0.012	0.82	0.89	<0.2	3.9	1.23	0.29	<0.1	<0.30	5.20	-19.5	-153	3.1
(AR) Absaroka Range - northeast of YNP, between northeast gate and Red Lodge, MT														
AR-1	--	0.014	<0.05	<0.2	<0.1	<0.01	--	<0.002	<0.1	<0.30	0.052	-19.0	-143	8.9
AR-2	--	0.015	<0.05	<0.2	<0.1	0.12	--	0.15	<0.1	<0.30	0.059	-19.3	-142	11.8
AR-3	--	0.022	<0.05	<0.2	<0.1	0.02	--	0.027	0.53	<0.30	0.175	-19.2	-145	8.2
AR-4.1	--	0.021	<0.05	<0.2	<0.1	0.01	--	<0.002	<0.1	<0.30	0.070	-18.9	-143	8.3
AR-4.2	--	0.025	<0.05	<0.2	<0.1	<0.01	<0.01	<0.002	<0.1	<0.30	0.086	-19.0	-142	9.5
AR-4.3	--	0.020	0.05	<0.03	<0.05	<0.01	0.001	<0.002	0.36	<0.05	0.065	-18.8	-140	10.5
AR-4.4	--	--	--	<0.03	<0.05	--	--	--	<0.02	0.05	--	-18.6	-141	7.8
AR-5	--	0.059	<0.05	<0.2	<0.1	<0.01	--	<0.002	2.6	<0.30	0.122	-19.3	-147	7.2
AR-6	--	--	--	<0.03	<0.05	--	--	--	0.41	<0.05	--	-19.1	-142	10.2

Table 4.--Physical and chemical analyses of cold water samples from the greater Yellowstone National Park area - continued

Site Name	Field Sample ID	Date	Temperature, water (Deg C)	Specific conductance (µS/cm)	pH (stand-ard units)	Silica, dissolved (mg/L as SiO ₂)	Calcium, dissolved (mg/L as Ca)	Magne-sium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potas-sium, dissolved (mg/L as K)	Alka-linity, lab (mg/L as HCO ₃)	Sulfate, dissolved (mg/L as SO ₄)	Chlo-ride, dissolved (mg/L as Cl)	Solids, sum of consti-tuents, dissolved (mg/L)
AR-7	91YNP-110	09-02-91	0	14	--	--	--	--	--	--	--	0.45	0.1	--
AR-8	91YNP-111	09-02-91	5	32	--	--	--	--	--	--	--	1.3	0.1	--
AR-9	91YNP-112	09-02-91	4	43	--	--	--	--	--	--	--	2.3	0.2	--
AR-10	91YNP-113	09-02-91	--	40	--	--	--	--	--	--	--	2.6	0.2	--
AR-11	91YNP-114	09-02-91	3.5	69	--	--	--	--	--	--	--	1.5	0.4	--
AR-12	91YNP-115	09-02-91	3	235	--	--	--	--	--	--	--	11.5	0.3	--
AR-13	91YNP-136	09-11-91	--	351	--	--	--	--	--	--	--	14.7	0.4	--
(AC) Absaroka Range - east of YNP eastgate, between east gate and Cody, WY														
AC-1	90YNP-241	06-09-90	10.5	1220	--	19.8	111	41.8	128	--	--	360	9.9	674
AC-2	90YNP-242	06-10-90	13.5	141	--	27.9	10.9	3.90	13.6	--	--	8.2	0.5	66
AC-3	90YNP-243	06-10-90	14	190	--	18.6	8.92	0.94	32.9	0.16	--	8.7	0.7	71
AC-4	90YNP-244	06-10-90	8.5	200	--	32.5	15.3	7.12	17.3	--	--	12.5	1.0	86
(AD) Absaroka Range - southern area, near Dubois, WY														
AD-1	90YNP-301	08-11-90	5	205	--	31.1	17.0	3.77	23.2	--	--	10.0	0.6	87
AD-2	90YNP-302	08-11-90	11	190	--	40.4	28.6	4.22	5.9	--	--	3.3	0.8	84
AD-3	90YNP-303	08-11-90	--	250	--	12.6	28.7	10.7	6.1	--	--	1.9	0.5	62
AD-4	90YNP-304	08-11-90	4	320	--	10.1	37.4	16.7	7.4	--	--	10.9	0.6	85
AD-5	90YNP-305	08-11-90	5	15	--	9.5	1.65	0.41	1.6	--	--	0.58	0.4	15
AD-6	90YNP-306	08-12-90	5	208	--	31.4	29.4	6.44	4.0	--	--	2.2	0.2	74
AD-7	90YNP-307	08-12-90	5	360	--	45.7	33.3	15.2	23.7	--	--	5.9	1.6	126
AD-8	90YNP-308	08-12-90	5.5	280	--	30.4	40.6	8.08	7.7	--	--	2.7	0.5	91
AD-9	90YNP-309	08-12-90	5	65	--	45.1	10.1	3.75	3.1	--	--	1.7	0.4	65
AD-10	90YNP-310	08-12-90	5	175	--	28.9	13.8	3.88	21.3	0.69	--	4.9	0.4	74
AD-11	90YNP-310A	08-12-90	--	--	--	--	--	--	--	--	--	--	--	--
AD-12	90YNP-311	08-13-90	4	325	--	17.1	24.4	16.2	30.1	--	--	15.9	1.0	106
AD-13	90YNP-312	08-13-90	7	335	--	20.6	32.5	21.4	5.2	--	--	3.7	0.4	85
AD-14	90YNP-313	08-13-90	8	430	--	16.2	51.2	18.2	13.5	--	--	4.5	1.1	106

Table 4. Physical and chemical analyses of cold water samples from the greater Yellowstone National Park area - continued

Site Name	Ammonium, dis-solved (mg/L as NH ₄)	Barium, dis-solved (mg/L as Ba)	Boron, dis-solved (mg/L as B)	Bromide, dis-solved (mg/L as Br)	Fluoride, dis-solved (mg/L as F)	Iron, dis-solved (mg/L as Fe)	Lithium, dis-solved (mg/L as Li)	Manganese, dis-solved (mg/L as Mn)	Nitrate, dis-solved (mg/L as NO ₃)	Phosphate, dis-solved (mg/L as PO ₄)	Strontium, dis-solved (mg/L as Sr)	O-18/O-16, stable isotope ratio (permil)	H-2/H-1, stable isotope ratio (permil)	d-parameter
AR-7	--	--	--	<0.03	<0.05	--	--	--	<0.02	<0.05	--	-19.7	-146	11.6
AR-8	--	--	--	<0.03	<0.05	--	--	--	<0.02	<0.05	--	-17.2	-125	12.8
AR-9	--	--	--	<0.03	<0.05	--	--	--	0.48	<0.05	--	-17.2	-126	11.4
AR-10	--	--	--	<0.03	0.13	--	--	--	1.1	<0.05	--	-15.5	-115	8.8
AR-11	--	--	--	<0.03	0.08	--	--	--	<0.01	<0.05	--	-15.5	-115	8.9
AR-12	--	--	--	<0.03	0.85	--	--	--	<0.01	<0.05	--	-20.2	-150	11.8
AR-13	--	--	--	<0.03	0.12	--	--	--	0.10	<0.05	--	-18.9	-141	9.7
(AC) Absaroka Range - east of YNP eastgate, between east gate and Cody, WY														
AC-1	--	0.015	0.17	<0.2	0.33	0.07	--	0.006	<0.1	<0.30	0.864	-19.1	-147	5.5
AC-2	--	<0.002	<0.05	<0.2	0.13	0.04	--	<0.002	<0.1	<0.30	0.070	-19.0	-146	5.7
AC-3	--	0.006	<0.05	<0.2	0.22	0.06	--	<0.002	<0.1	<0.30	0.093	-18.3	-145	1.3
AC-4	--	<0.002	<0.05	<0.2	0.14	<0.01	--	<0.002	<0.1	<0.30	0.048	-17.7	-140	1.1
(AD) Absaroka Range - southern area, near Dubois, WY														
AD-1	--	0.026	<0.05	<0.2	0.20	0.07	<0.01	0.015	<0.1	<0.30	0.098	-19.2	-145	8.8
AD-2	--	0.084	<0.05	<0.2	<0.1	0.02	<0.01	<0.002	<0.1	<0.30	0.152	-18.9	-144	6.8
AD-3	--	0.13	<0.05	<0.2	<0.1	0.05	<0.01	0.009	<0.1	<0.30	0.350	-19.3	-145	9.2
AD-4	--	0.11	<0.05	<0.2	0.18	<0.01	<0.01	<0.002	0.70	<0.30	0.289	-19.3	-146	9.2
AD-5	--	0.004	<0.05	<0.2	<0.1	<0.01	<0.01	<0.002	0.55	<0.30	0.010	-18.3	-137	9.7
AD-6	--	0.097	<0.05	<0.2	<0.1	<0.01	<0.01	<0.002	<0.1	<0.30	0.096	-18.6	-139	9.2
AD-7	--	0.17	<0.05	<0.2	0.18	<0.01	<0.01	<0.002	<0.1	<0.30	0.339	-19.0	-149	3.2
AD-8	--	0.11	<0.05	<0.2	<0.1	<0.01	<0.01	<0.002	<0.1	<0.30	0.115	-18.5	-142	5.8
AD-9	--	0.091	<0.05	<0.2	<0.1	<0.01	<0.01	<0.002	<0.1	<0.30	0.063	-19.2	-144	9.1
AD-10	--	0.031	<0.05	<0.2	<0.1	<0.01	<0.01	<0.002	<0.1	<0.30	0.092	-17.9	-136	7.1
AD-11	--	--	--	--	--	--	--	--	--	--	--	-18.1	-136	8.9
AD-12	--	0.070	<0.05	<0.2	0.16	<0.01	<0.01	<0.002	<0.1	<0.30	0.486	-19.0	-148	3.3
AD-13	--	0.19	<0.05	<0.2	0.11	<0.01	<0.01	<0.002	<0.1	<0.30	0.339	-19.3	-149	4.8
AD-14	--	0.12	<0.05	<0.2	0.17	0.12	0.042	0.010	<0.1	<0.30	0.325	-18.8	-145	5.3

Table 4.--Physical and chemical analyses of cold water samples from the greater Yellowstone National Park area - continued

[illegible]

Table 4. Physical and chemical analyses of cold water samples from the greater Yellowstone National Park area - continued

Site Name	Ammo-nium, dis-solved (mg/L as NH ₄)	Barium, dis-solved (mg/L as Ba)	Boron, dis-solved (mg/L as B)	Bromide, dis-solved (mg/L as Br)	Fluo-ride, dis-solved (mg/L as F)	Iron, dis-solved (mg/L as Fe)	Lithium, dis-solved (mg/L as Li)	Manga-nese, dis-solved (mg/L as Mn)	Nitrate, dis-solved (mg/L as NO ₃)	Phos-phate, dis-solved (mg/L as PO ₄)	Stron-tium, dis-solved (mg/L as Sr)	O-18/ O-16, stable isotope ratio (permil)	H-2/ H-1, stable isotope ratio (permil)	d-para-meter
(AG) Absaroka Range - Gardiner-Mammoth area														
AG-1.1	--	--	--	--	--	--	--	--	--	--	--	-18.1	-142	3.4
AG-1.2	0.12	0.025	0.21	0.03	0.43	<0.01	0.053	<0.002	1.9	<0.05	0.355	-17.4	-140	-0.9
AG-2	--	--	--	--	--	--	--	--	--	--	--	-19.6	-152	4.8
AG-3	--	--	--	--	--	--	--	--	--	--	--	-19.0	-143	9.5
AG-4	--	--	--	--	--	--	--	--	--	--	--	-18.9	-144	6.9
AG-5.1	--	0.017	<0.05	<0.03	<0.05	0.05	--	<0.002	0.05	<0.05	0.052	-19.1	-142	10.3
AG-5.2	--	0.011	<0.05	<0.03	<0.05	0.02	<0.001	<0.002	1.2	0.08	0.046	-19.1	-142	10.3
AG-5.3	--	--	--	<0.03	<0.05	--	--	--	<0.02	0.05	--	-17.1	-138	-1.3
AG-6.1	--	0.068	<0.05	<0.03	0.71	<0.01	--	0.004	1.06	<0.05	0.124	-20.2	-152	9.7
AG-6.2	--	--	--	--	--	--	--	--	--	--	--	-20.0	-147	12.6
AG-7	--	0.015	<0.05	<0.03	<0.05	0.13	--	0.003	<0.02	<0.05	0.015	-19.1	-142	10.7
AG-8	--	0.020	<0.05	<0.03	<0.05	0.02	--	<0.002	0.06	<0.05	0.016	-19.7	-146	12.0
AG-9.1	--	0.063	<0.05	<0.03	0.14	<0.01	--	<0.002	<0.02	<0.05	0.231	-19.6	-150	7.2
AG-9.2	--	--	--	--	--	--	--	--	--	--	--	-19.7	-149	8.3
AG-9.3	--	0.035	<0.05	<0.03	0.12	<0.01	0.013	<0.002	0.05	<0.05	0.200	-19.1	-147	5.5
AG-10.1	--	--	--	--	--	--	--	--	--	--	--	-19.6	-152	5.5
AG-10.2	0.10	0.053	<0.05	0.04	0.55	<0.01	0.058	<0.002	0.25	<0.05	0.323	-19.2	-152	1.9
AG-10.3	--	--	--	--	--	--	--	--	--	--	--	-19.8	-152	6.4
AG-11.1	--	0.066	<0.05	<0.03	0.16	<0.01	--	<0.002	1.2	<0.05	1.32	-19.1	-148	4.6
AG-11.2	--	0.059	<0.05	0.04	0.14	<0.01	0.011	<0.002	1.5	<0.05	1.24	-19.1	-149	3.9
AG-11.3	--	--	--	<0.03	0.15	--	--	--	1.4	<0.05	--	-18.9	-147	3.7
AG-12	--	--	--	--	--	--	--	--	--	--	--	-19.6	-150	6.6
AG-13	--	--	--	--	--	--	--	--	--	--	--	-19.8	-152	6.9
AG-14	--	--	--	--	--	--	--	--	--	--	--	-19.1	-144	9.6
AG-15	--	0.014	0.29	0.12	3.3	0.05	0.24	0.31	1.2	<0.05	2.11	-18.8	-146	5.1
(YP) Yellowstone Plateau - including interior volcanic plateaus and Washburn Range														
YP-1.1	--	0.016	0.07	0.03	3.3	0.04	--	0.016	<0.02	<0.05	0.039	-19.6	-148	8.4
YP-1.2	--	--	--	--	--	--	--	--	--	--	--	-19.6	-149	7.2

Table 4. Physical and chemical analyses of cold water samples from the greater Yellowstone National Park area - continued

Site Name	Ammo-nium, dis-solved (mg/L as NH ₄)	Barium, dis-solved (mg/L as Ba)	Boron, dis-solved (mg/L as B)	Bromide, dis-solved (mg/L as Br)	Fluo-ride, dis-solved (mg/L as F)	Iron, dis-solved (mg/L as Fe)	Lithium, dis-solved (mg/L as Li)	Manga-nese, dis-solved (mg/L as Mn)	Nitrate, dis-solved (mg/L as NO ₃)	Phos-phate, dis-solved (mg/L as PO ₄)	Stron-tium, dis-solved (mg/L as Sr)	O-18/ O-16, stable isotope ratio (permil)	H-2/ H-1, stable isotope ratio (permil)	d-para-meter
YP-1.3	--	--	--	--	--	--	--	--	--	--	--	-19.6	-150	7.3
YP-2	--	0.037	<0.05	<0.2	<0.1	<0.01	--	0.007	<0.1	<0.30	0.099	-18.5	-143	4.2
YP-3.1	--	0.008	<0.05	<0.2	0.54	0.02	--	<0.002	<0.1	<0.30	0.045	-19.8	-150	8.0
YP-3.2	--	0.025	<0.05	<0.2	0.49	0.03	<0.01	<0.002	0.94	<0.30	0.085	-18.9	-147	3.8
YP-3.3	--	0.008	<0.05	<0.03	0.63	<0.01	0.004	<0.002	1.7	<0.08	0.048	-19.9	-150	8.8
YP-3.4	--	--	--	<0.03	0.65	--	--	--	1.4	0.13	--	-19.9	-150	9.1
YP-3.5	--	--	--	--	--	--	--	--	--	--	--	-19.7	-148	9.5
YP-4.1	--	0.002	<0.05	<0.2	3.2	0.06	--	<0.002	0.18	<0.30	0.013	-19.2	-148	5.6
YP-4.2	--	0.002	<0.05	<0.03	4.3	0.03	0.017	<0.002	0.23	<0.05	0.015	-19.8	-148	10.4
YP-5	--	0.041	<0.05	<0.2	3.8	4.2	--	0.29	<0.1	<0.30	0.027	-19.6	-147	9.3
YP-6.1	--	0.002	0.21	<0.2	5.2	<0.01	--	<0.002	0.75	<0.30	0.007	-19.4	-149	6.3
YP-6.2	--	--	--	--	--	--	--	--	--	--	--	-19.4	-148	7.0
YP-6.3	--	--	--	0.04	7.1	--	--	--	0.80	<0.05	--	-19.5	-150	6.1
YP-6.4	--	--	--	--	--	--	--	--	--	--	--	-19.5	-149	6.6
YP-7	--	0.009	0.31	<0.2	3.0	0.04	--	0.008	0.37	<0.30	0.073	-19.1	-147	5.9
YP-8	--	0.003	<0.05	<0.2	1.4	0.05	<0.01	<0.002	0.82	<0.30	0.013	-18.3	-139	7.7
YP-9	--	0.026	<0.05	<0.2	<0.1	0.01	<0.01	<0.002	0.20	<0.30	0.067	-19.1	-146	6.5
(GG) Gallatin Range - Gardiner-Mammoth area														
GG-1.1	--	--	--	--	--	--	--	--	--	--	--	-17.8	-142	0.7
GG-1.2	--	0.084	<0.05	<0.03	0.27	0.02	0.011	0.010	<0.02	0.12	0.563	-18.3	-142	4.5
GG-1.3	--	--	--	<0.03	0.29	--	--	--	<0.02	0.06	--	-18.1	-141	3.9
GG-1.4	--	--	--	--	--	--	--	--	--	--	--	-17.9	-138	4.7
GG-2	--	--	--	--	--	--	--	--	--	--	--	-18.2	-142	3.3
GG-3	--	--	--	--	--	--	--	--	--	--	--	-19.7	-146	11.6
GG-4	--	--	--	--	--	--	--	--	--	--	--	-19.1	-146	6.6
GG-5	--	--	--	--	--	--	--	--	--	--	--	-20.3	-152	9.7
GG-6	--	--	--	--	--	--	--	--	--	--	--	-19.7	-149	8.7
GG-7	--	0.22	<0.05	<0.03	0.05	<0.01	--	<0.002	<0.02	<0.05	0.100	-19.3	-147	7.8
GG-8	--	0.043	<0.05	<0.03	0.05	<0.01	--	<0.002	<0.02	<0.05	0.082	-19.6	-147	10.1
GG-9	--	--	--	--	--	--	--	--	--	--	--	-19.3	-144	10.4

Table 4. Physical and chemical analyses of cold water samples from the greater Yellowstone National Park area - continued

Site Name	Ammo-nium, dis-solved (mg/L as NH ₄)	Barium, dis-solved (mg/L as Ba)	Boron, dis-solved (mg/L as B)	Bromide, dis-solved (mg/L as Br)	Fluo-ride, dis-solved (mg/L as F)	Iron, dis-solved (mg/L as Fe)	Lithium, dis-solved (mg/L as Li)	Manga-nese, dis-solved (mg/L as Mn)	Nitrate, dis-solved (mg/L as NO ₃)	Phos-phate, dis-solved (mg/L as PO ₄)	Stron-tium, dis-solved (mg/L as Sr)	O-18/ O-16, stable isotope ratio (permil)	H-2/ H-1, stable isotope ratio (permil)	d-para-meter
GG-10.1	--	--	--	--	--	--	--	--	--	--	--	-19.9	-149	10.0
GG-10.2	0.12	0.018	0.31	<0.03	3.0	0.14	0.20	0.015	<0.02	<0.05	0.037	-18.8	-148	2.5
GG-11	--	--	--	--	--	--	--	--	--	--	--	-19.0	-146	5.3
GG-12	--	0.005	<0.05	<0.2	4.8	<0.01	--	0.011	0.12	<0.30	0.061	-18.5	-146	1.9
GG-13	--	0.018	<0.05	<0.2	0.80	<0.01	--	0.004	1.3	<0.30	0.105	-19.0	-144	8.4
GG-14.1	--	0.092	<0.05	<0.03	0.23	<0.01	0.010	<0.002	<0.02	0.10	0.449	-17.9	-140	3.6
GG-14.2	--	--	--	<0.03	0.25	--	--	--	<0.01	0.13	--	-18.1	-140	4.8
GG-14.3	--	--	--	--	--	--	--	--	--	--	--	-17.6	-137	3.6
GG-15	--	0.076	<0.05	<0.03	0.07	<0.01	0.003	0.004	0.18	<0.05	0.088	-18.5	-141	7.5
(GN) Gallatin Range - northern area														
GN-1	--	0.17	<0.05	<0.03	0.33	<0.01	--	<0.002	<0.02	<0.05	0.286	-19.5	-145	11.1
GN-2	--	--	--	--	--	--	--	--	--	--	--	-19.4	-149	6.1
GN-3	--	0.010	<0.05	<0.03	0.10	<0.01	--	<0.002	<0.02	<0.05	0.098	-19.5	-149	6.3
GN-4	--	--	--	--	--	--	--	--	--	--	--	-19.3	-149	5.4
GN-5	--	0.050	<0.05	<0.03	0.16	<0.01	--	<0.002	<0.02	0.33	0.241	-19.3	-148	6.7
GN-6	--	--	--	--	--	--	--	--	--	--	--	-18.9	-143	8.4
GN-7	--	--	--	--	--	--	--	--	--	--	--	-19.2	-145	8.5
GN-8	--	--	--	--	--	--	--	--	--	--	--	-19.0	-142	10.5
GN-9	--	0.027	<0.05	<0.2	0.11	1.0	--	0.007	0.14	<0.30	0.033	-18.5	-142	6.2
GN-10	--	0.022	<0.05	<0.2	0.13	0.03	--	0.053	0.33	<0.30	0.183	-19.3	-148	6.7
GN-11	--	0.027	<0.05	<0.2	<0.1	<0.01	--	<0.002	<0.1	<0.30	0.043	-19.3	-145	9.5
GN-12	--	0.014	<0.05	<0.2	0.12	<0.01	--	<0.002	<0.1	<0.30	0.254	-19.0	-148	3.7
GN-13	--	0.037	<0.05	<0.2	<0.1	<0.01	--	<0.002	<0.1	<0.30	0.104	-19.3	-147	7.1
GN-14	--	--	--	--	--	--	--	--	--	--	--	-18.1	-142	3.2
GN-15	--	0.027	<0.05	<0.2	0.10	<0.01	--	<0.002	<0.1	<0.30	0.065	-18.7	-143	6.4
GN-16	--	--	--	--	--	--	--	--	--	--	--	-17.9	-143	0.3
(MR) Madison Range - northwest of YNP														
MR-1	--	0.037	<0.05	<0.2	<0.1	<0.01	0.01	<0.002	0.69	<0.30	0.073	-18.6	-144	5.1
MR-2	--	--	--	--	--	--	--	--	--	--	--	-17.0	-135	1.3

Table 4.--Physical and chemical analyses of cold water samples from the greater Yellowstone National Park area - continued

Site Name	Field Sample ID	Date	Temperature, water (Deg C)	Specific conductance (µS/cm)	pH (stand-ard units)	Silica, dissolved (mg/L as SiO ₂)	Calcium, dissolved (mg/L as Ca)	Magne-sium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potas-sium, dissolved (mg/L as K)	Alka-linity, lab (mg/L as HCO ₃)	Sulfate, dissolved (mg/L as SO ₄)	Chlo-ride, dissolved (mg/L as Cl)	Solids, sum of consti-tuents, dissolved (mg/L)
MR-3	90YNP-322	08-16-90	5	52	--	9.2	8.16	2.09	2.1	--	--	3.9	0.3	27
MR-4	90YNP-323	08-17-90	10	350	--	27.9	35.4	12.3	22.1	--	--	17.3	13.6	132
MR-5	90YNP-324	08-17-90	15	340	--	31.6	34.4	11.1	19.0	--	--	29.9	9.1	139
MR-6	90YNP-325	08-17-90	9	75	--	21.3	10.3	2.83	3.2	--	--	4.0	1.0	44
MR-7	90YNP-326	08-18-90	1	22	--	2.8	3.13	0.43	0.4	--	--	0.6	0.2	9
MR-8.1	90YNP-327	08-18-90	2	30	--	4.7	4.89	0.67	0.6	--	--	1.1	0.1	13
MR-8.2	91YNP-103	09-01-91	4	37	--	--	--	--	--	--	--	1.2	0.1	--
MR-9	90YNP-328	08-18-90	4	232	--	4.7	37.8	6.88	0.5	--	--	5.1	0.4	57
MR-10	90YNP-329	08-19-90	6	130	--	14.3	20.4	4.30	1.8	--	--	2.6	0.5	44
MR-11	90YNP-330	08-19-90	7	250	--	9.7	40.3	7.99	1.1	--	--	5.2	0.4	65
MR-12	90YNP-331	08-19-90	10	320	--	13.2	31.0	17.3	8.0	2.09	--	3.8	3.1	79
MR-13	90YNP-332	08-19-90	8	220	--	11.1	25.3	11.9	5.0	1.83	--	2.2	2.4	59
MR-14	90YNP-333	08-19-90	5	225	--	11.7	24.2	11.9	5.3	--	--	2.2	2.4	59
MR-15	90YNP-335	08-19-90	13	230	--	12.0	24.1	11.8	5.3	--	--	2.1	2.3	59
MR-16	90YNP-336	08-19-90	9	240	--	17.6	26.4	14.9	8.7	--	--	2.8	2.2	74
MR-17	91YNP-104	09-01-91	0	29	--	--	--	--	--	--	--	1.0	0.2	--
MR-18	91YNP-105	09-01-91	4	44	--	--	--	--	--	--	--	3.1	0.2	--
MR-19	91YNP-107	09-01-91	8	33	--	--	--	--	--	--	--	2.0	0.2	--
(SR) Snake River Plain - southwest of YNP														
SR-1	90YNP-201	06-02-90	8	170	--	37.0	19.3	4.83	7.4	--	--	3.6	5.1	78
SR-2	90YNP-202	06-02-90	9	59	--	28.9	5.40	1.29	3.4	1.11	--	2.5	1.4	49
SR-3	90YNP-203	06-03-90	6	56	--	6.6	4.68	1.26	2.9	--	--	1.3	2.3	20
SR-4	90YNP-204	06-03-90	6	85	--	25.2	9.36	2.76	3.3	--	--	2.1	0.9	44
SR-5	90YNP-205	06-03-90	5	46	--	16.8	4.89	1.12	2.2	--	--	1.4	0.4	27
SR-6	90YNP-206	06-03-90	--	49	--	18.5	4.48	1.26	2.7	--	--	2.0	1.0	31
SR-7	90YNP-207	06-03-90	6	99	--	39.1	7.34	3.23	5.8	--	--	1.5	1.1	60
SR-8	90YNP-208	06-03-90	5.5	86	--	36.8	6.80	3.36	3.4	--	--	1.5	1.0	54
SR-9	90YNP-209	06-03-90	10.5	95	--	40.6	4.19	0.66	12.5	--	--	2.2	2.1	66
SR-10	90YNP-210	06-04-90	5	29	--	22.8	1.57	0.43	1.3	--	--	1.5	1.1	32
SR-11.1	90YNP-211	06-04-90	14	130	--	49.9	5.29	0.76	18.8	--	--	2.8	3.8	86

Table 4. Physical and chemical analyses of cold water samples from the greater Yellowstone National Park area - continued

Site Name	Ammonium, dissolved (mg/L as NH ₄)	Barium, dissolved (mg/L as Ba)	Boron, dissolved (mg/L as B)	Bromide, dissolved (mg/L as Br)	Fluoride, dissolved (mg/L as F)	Iron, dissolved (mg/L as Fe)	Lithium, dissolved (mg/L as Li)	Manganese, dissolved (mg/L as Mn)	Nitrate, dissolved (mg/L as NO ₃)	Phosphate, dissolved (mg/L as PO ₄)	Strontium, dissolved (mg/L as Sr)	O-18/O-16, stable isotope ratio (permil)	H-2/H-1, stable isotope ratio (permil)	d-parameter
MR-3	--	0.010	<0.05	<0.2	<0.1	0.08	<0.01	0.088	0.53	<0.30	0.040	-18.2	-138	8.1
MR-4	--	0.043	0.13	<0.2	1.3	0.02	0.13	0.010	1.0	<0.30	0.119	-17.4	-135	4.1
MR-5	--	0.025	<0.05	<0.2	0.58	<0.01	0.016	<0.002	2.6	<0.30	0.235	-18.5	-146	2.4
MR-6	--	0.037	<0.05	<0.2	<0.1	0.39	<0.01	0.005	<0.1	<0.30	0.039	-18.7	-142	7.5
MR-7	--	0.003	<0.05	<0.2	<0.1	<0.01	<0.01	<0.002	0.90	<0.30	0.011	-19.1	-140	13.2
MR-8.1	--	0.008	<0.05	<0.2	<0.1	<0.01	<0.01	<0.002	0.42	<0.30	0.026	-19.7	-147	11.0
MR-8.2	--	--	--	<0.03	<0.05	--	--	--	0.64	<0.05	--	-19.0	-143	9.1
MR-9	--	0.14	<0.05	<0.2	<0.1	<0.01	<0.01	<0.002	0.83	<0.30	0.069	-19.3	-147	7.9
MR-10	--	0.024	<0.05	<0.2	<0.1	<0.01	<0.01	<0.002	<0.1	<0.30	0.033	-18.3	-135	10.8
MR-11	--	0.052	<0.05	<0.2	<0.1	<0.01	<0.01	<0.002	<0.1	<0.30	0.059	-18.8	-139	11.7
MR-12	--	0.023	<0.05	<0.2	0.11	<0.01	<0.01	<0.002	1.6	<0.30	0.057	-19.3	-147	7.6
MR-13	--	0.014	<0.05	<0.2	0.23	<0.01	<0.01	<0.002	0.43	<0.30	0.058	-17.2	-136	1.8
MR-14	--	0.014	<0.05	<0.2	0.29	<0.01	<0.01	<0.002	0.41	<0.30	0.055	-17.2	-136	1.8
MR-15	--	0.015	<0.05	<0.2	0.27	<0.01	<0.01	<0.002	0.55	<0.30	0.057	-17.1	-131	6.1
MR-16	--	0.008	<0.05	<0.2	0.18	<0.01	<0.01	<0.002	1.1	<0.30	0.058	-19.4	-148	7.0
MR-17	--	--	--	<0.03	<0.05	--	--	--	2.1	<0.05	--	-18.0	-134	10.0
MR-18	--	--	--	<0.03	<0.05	--	--	--	0.25	<0.05	--	-18.4	-136	11.0
MR-19	--	--	--	<0.03	<0.05	--	--	--	<0.01	<0.05	--	-18.0	-134	10.4
(SR) Snake River Plain - southwest of YNP														
SR-1	--	0.018	0.08	<0.2	0.2	0.03	--	0.003	0.31	<0.30	0.051	-17.7	-136	5.3
SR-2	--	0.016	0.05	<0.2	<0.1	0.26	--	0.008	4.2	<0.30	0.019	-17.4	-134	5.5
SR-3	--	0.012	<0.05	<0.2	<0.1	0.15	--	0.045	0.80	<0.30	0.032	-17.1	-130	6.8
SR-4	--	0.004	<0.05	<0.2	<0.1	0.22	--	<0.002	<0.1	<0.30	0.036	-17.4	-130	9.3
SR-5	--	0.009	<0.05	<0.2	<0.1	0.10	--	<0.002	<0.1	<0.30	0.029	-17.6	-130	10.7
SR-6	--	0.005	<0.05	<0.2	<0.1	0.15	--	<0.002	<0.1	<0.30	0.024	-17.8	-129	13.4
SR-7	--	0.008	0.06	<0.2	1.3	0.20	--	<0.002	0.2	<0.30	0.022	-18.2	-133	12.1
SR-8	--	0.004	<0.05	<0.2	<0.1	0.12	--	<0.002	<0.1	<0.30	0.022	-18.1	-132	12.8
SR-9	--	<0.002	0.07	<0.2	2.6	0.02	--	<0.002	0.31	<0.30	0.006	-18.5	-135	12.8
SR-10	--	<0.002	<0.05	<0.2	<0.1	<0.01	--	<0.002	2.7	<0.30	0.011	-18.7	-137	13.1
SR-11.1	--	<0.002	0.09	<0.2	3.4	<0.01	--	<0.002	<0.1	<0.30	0.006	-18.5	-137	11.6

Table 4. Physical and chemical analyses of cold water samples from the greater Yellowstone National Park area - continued

Site Name	Ammo- nium, dis- solved (mg/L as NH ₄)	Barium, dis- solved (mg/L as Ba)	Boron, dis- solved (mg/L as B)	Bromide, dis- solved (mg/L as Br)	Fluo- ride, dis- solved (mg/L as F)	Iron, dis- solved (mg/L as Fe)	Lithium, dis- solved (mg/L as Li)	Manga- nese, dis- solved (mg/L as Mn)	Nitrate, dis- solved (mg/L as NO ₃)	Phos- phate, dis- solved (mg/L as PO ₄)	Stron- tium, dis- solved (mg/L as Sr)	O-18/ O-16, stable isotope ratio (permil)	H-2/ H-1, stable isotope ratio (permil)	d-para- meter
SR-11.2	--	--	--	--	--	--	--	--	--	--	--	-18.6	-138	10.8
SR-11.3	--	<0.002	0.08	<0.03	4.6	<0.01	0.080	<0.002	0.15	<0.05	0.006	-18.5	-137	10.4
SR-11.4	--	--	--	<0.03	4.9	--	--	--	<0.02	<0.05	--	-18.2	-139	6.8
SR-12.1	--	--	--	--	--	--	--	--	--	--	--	-18.5	-136	12.2
SR-12.2	--	<0.002	0.06	<0.03	4.0	<0.01	0.060	<0.002	0.16	<0.05	0.006	-18.4	-137	10.5
SR-12.3	--	--	--	<0.03	4.2	--	--	--	<0.02	<0.05	--	-18.2	-138	8.1
SR-13	--	<0.002	<0.05	<0.2	2.1	0.02	--	<0.002	<0.1	<0.30	0.006	-18.5	-135	12.8
SR-14	--	0.003	<0.05	<0.2	<0.1	0.08	--	<0.002	<0.1	<0.30	0.106	-18.2	-130	15.1
SR-15	--	<0.002	0.08	<0.2	2.9	0.02	--	<0.002	<0.1	<0.30	0.008	-18.8	-141	8.9
SR-16	--	--	--	--	--	--	--	--	--	--	--	-17.6	-137	4.5

Table 5.--Physical and chemical analyses of snow samples from the greater Yellowstone National Park area
[Deg C, degrees Celsius; $\mu\text{S}/\text{cm}$, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter;
--, not determined; <, less than]

Site Name	Field Sample ID	Date	Specific conductance ($\mu\text{S}/\text{cm}$)	Sulfate, dis-solved (mg/L as SO_4)	Chloride, dis-solved (mg/L as Cl)	Bromide, dis-solved (mg/L as Br)	Fluoride, dis-solved (mg/L as F)	Nitrate, dis-solved (mg/L as NO_3)	Phosphate, dis-solved (mg/L as PO_4)	O-18/O-16, stable isotope ratio (permil)	H-2/H-1, stable isotope ratio (permil)	d-parameter
(AR-S) Absaroka Range - northeast of YNP, between northeast gate and Red Lodge, MT												
AR-S1	90YNP-258	06-09-90	--	--	--	--	--	--	--	-21.5	-162	10.4
AR-S2	91YNP-9	05-26-91	2	--	--	--	--	--	--	-22.2	-167	10.9
AR-S3	91YNP-10	05-26-91	2	--	--	--	--	--	--	-19.6	-145	11.9
AR-S4.1	91YNP-11	05-26-91	3	--	--	--	--	--	--	-19.1	-141	11.7
AR-S4.2	91YNP-11A	05-26-91	--	--	--	--	--	--	--	-22.6	-170	10.3
AR-S5.1	91YNP-12	05-26-91	2	--	--	--	--	--	--	-19.9	-146	13.1
AR-S5.2	91YNP-12A	05-26-91	--	--	--	--	--	--	--	-23.6	-178	10.8
AR-S6	91YNP-13	05-26-91	3	--	--	--	--	--	--	-21.2	-160	9.8
AR-S7.1	91YNP-14	05-26-91	2	--	--	--	--	--	--	-20.9	-158	9.3
AR-S7.2	91YNP-14A	05-26-91	--	--	--	--	--	--	--	-22.2	-169	8.7
AR-S8.1	91YNP-15	05-26-91	3	--	--	--	--	--	--	-20.8	-157	9.8
AR-S8.2	91YNP-15A	05-26-91	--	--	--	--	--	--	--	-20.3	-153	9.3
(YP-S) Yellowstone Plateau - including interior volcanic plateaus and Washburn Range												
YP-S1.1	91YNP-16	05-26-91	3	--	--	--	--	--	--	-17.8	-133	8.9
YP-S1.2	91YNP-16A	05-26-91	--	--	--	--	--	--	--	-16.6	-121	12.0
YP-S1.3	91YNP-145	09-14-91	4.5	0.08	0.3	<0.03	<0.05	0.10	<0.05	-19.1	-140	13.1
YP-S2	91YNP-18	05-27-91	4	--	--	--	--	--	--	-18.5	-137	10.9
YP-S3.1	91YNP-19	05-27-91	4	--	--	--	--	--	--	-18.7	-138	11.5
YP-S3.2	91YNP-19A	05-27-91	--	--	--	--	--	--	--	-12.5	-88	11.8
YP-S4	91YNP-20	05-27-91	4	--	--	--	--	--	--	-18.2	-136	9.8
YP-S5	91YNP-21	05-27-91	5	--	--	--	--	--	--	-23.9	-175	16.0
YP-S6	91YNP-22	05-27-91	3	--	--	--	--	--	--	-22.3	-167	11.3
YP-S7	91YNP-23	05-27-91	3	--	--	--	--	--	--	-19.9	-147	11.5
YP-S8	91YNP-25A	05-28-91	6	--	--	--	--	--	--	-21.7	-164	9.3
YP-S9	91YNP-142	09-14-91	12	0.56	0.4	<0.03	<0.05	<0.02	<0.05	-17.9	-128	15.2
YP-S10	91YNP-143	09-14-91	7	--	--	--	--	--	--	-18.1	-130	14.5

Table 5.--Physical and chemical analyses of snow samples from the greater Yellowstone National Park area - continued

Site Name	Field Sample ID	Date	Specific conductance (μS/cm)	Sulfate, dis-solved (mg/L as SO ₄)	Chloride, dis-solved (mg/L as Cl)	Bromide, dis-solved (mg/L as Br)	Fluoride, dis-solved (mg/L as F)	Nitrate, dis-solved (mg/L as NO ₃)	Phosphate, dis-solved (mg/L as PO ₄)	O-18/O-16, stable isotope ratio (permil)	H-2/H-1, stable isotope ratio (permil)	d-parameter
YP-S11	91YNP-144	09-14-91	3	--	--	--	--	--	--	-19.1	-143	9.7
YP-S12	91YNP-146	09-14-91	2.0	0.06	0.1	<0.03	<0.05	0.06	<0.05	-19.2	-141	12.6
YP-S13	91YNP-147	09-14-91	7	--	--	--	--	--	--	-19.4	-141	14.6
YP-S14	91YNP-148	09-14-91	9	--	--	--	--	--	--	-19.6	-143	13.8
YP-S15.1	91YNP-149	09-14-91	8	--	--	--	--	--	--	-17.2	-122	15.3
YP-S15.2	91YNP-150	09-14-91	7.5	0.9	0.3	<0.03	<0.05	0.21	<0.05	-18.2	-133	12.6
(MR-S) Madison Range - Beehive basin, near Lone Mountain ski area, MT												
MR-S1	91YNP-3	05-25-91	8	--	--	--	--	--	--	-19.4	-146	8.6
MR-S2	91YNP-4	05-25-91	3	--	--	--	--	--	--	-19.4	-146	9.3
MR-S3	91YNP-5	05-25-91	3	--	--	--	--	--	--	-20.3	-152	10.4
MR-S4	91YNP-6	05-25-91	5	--	--	--	--	--	--	-17.9	-134	9.1
MR-S5	91YNP-7	05-25-91	2	--	--	--	--	--	--	-19.8	-148	10.5
MR-S6-A	91YNP-35A	05-25-91	--	--	--	--	--	--	--	-19.1	-140	12.3
MR-S6-B	91YNP-35B	05-25-91	--	--	--	--	--	--	--	-23.2	-175	10.7
MR-S6-C	91YNP-35C	05-25-91	--	--	--	--	--	--	--	-18.4	-136	10.7
MR-S6-D	91YNP-35D	05-25-91	--	--	--	--	--	--	--	-18.6	-134	14.2

Table 6.--Physical and chemical analyses of thermal and mineral water samples from the greater Yellowstone National Park area
[Deg C, degrees Celsius; $\mu\text{S}/\text{cm}$, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; --, not determined; <, less than]

Site Name	Field Sample ID	Date	Temperature, water (Deg C)	Specific conductance ($\mu\text{S}/\text{cm}$)	pH (standard units)	Silica, dissolved (mg/L as SiO_2)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Alkalinity, lab (mg/L as HCO_3)	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)	Solids, sum of constituents, dissolved (mg/L)
<i>Sites inside Yellowstone National Park boundary</i>														
(M) Mammoth Area														
M-NG.1	89YNP-101	06-20-89	72	2440	6.51	57.4	384	70.3	130	56.3	897	573	164	2361
M-NG.2	89YNP-301	09-08-89	68	2450	6.5	58.9	347	70.6	129	56.1	816	583	164	2252
M-NG.3	90YNP-101	06-11-90	59	2400	6.42	53.0	313	77.7	126	56.6	720	581	166	2121
M-OT	89YNP-302	09-08-89	71	2380	6.45	57.0	328	72.7	126	54.9	746	582	161	2154
M-PP	90YNP-103	06-11-90	--	2500	6.76	55.0	337	76.7	124	54.9	747	640	163	2224
M-PS	90YNP-104	06-11-90	44	2450	6.08	49.3	337	69.1	125	55.2	595	711	162	2130
M-SP.1	89YNP-253	06-25-89	8	541	5.77	20.3	102	8.25	1.0	1.23	--	23.7	1.1	159
M-SP.2	90YNP-107	06-12-90	--	585	--	17.8	115	9.07	1.1	1.08	378	19.9	0.9	543
M-Y10.1	89YNP-102	06-20-89	53	3030	6.21	94.6	492	76.1	156	64.5	1040	808	174	2938
M-Y10.2	89YNP-304	09-09-89	60	3020	6.34	95.9	504	78.7	158	64.6	1040	815	174	2961
M-Y10.3	90YNP-4	05-18-90	70	3160	--	91.7	490	84.0	159	63.3	1160	802	183	3076
M-Y10.4	90YNP-5	05-18-90	70	3060	--	92.4	471	84.9	160	64.1	1040	808	180	2942
M-Y10.5	90YNP-102	06-11-90	52	3010	6.3	88.8	466	85.4	156	63.3	1030	810	175	2911
(NM) Norris-Mammoth Corridor														
NM-AS1	91YNP-56	05-28-91	82	2680	2.09	101	1.82	0.25	13.8	5.73	--	427	2.2	566
NM-AS2	91YNP-57	05-28-91	93	3900	2.09	207	1.26	0.48	22.3	11.6	--	719	0.5	972
NM-CW1	89YNP-336	09-13-89	85	1210	--	243	21.4	5.19	167	47.6	--	92.0	286	893
NM-CW2	89YNP-337	09-13-89	86	929	--	250	13.5	3.36	122	49.2	--	108	184	752
NM-CW3.1	89YNP-28	05-18-89	--	--	--	--	--	--	--	--	--	--	--	--
NM-CW3.2	89YNP-106	06-22-89	92.6	1470	6.75	304	13.6	0.12	278	64.0	33	64.8	467	1278
NM-CW3.3	89YNP-338	09-13-89	94	1710	--	294	12.3	0.07	272	62.7	--	70.5	443	1203
NM-CW3.4	90YNP-118	06-15-90	94.8	1600	6.88	284	11.5	0.10	258	60.0	42	69.8	425	1198
NM-HB	89YNP-116	06-24-89	33.5	2760	6.34	18.5	156	44.1	458	34.5	1500	218	140	2605
NM-S.1	89YNP-118	06-26-89	--	1260	6.51	83.6	141	12.9	93.5	36.4	570	84.5	97.0	1137
NM-S.2	89YNP-215	06-26-89	73		6.2	--	--	--	--	--	--	--	--	--
NM-W	91YNP-28	05-29-91	92.7	1310	2.53	79.0	2.63	0.60	2.9	4.49	--	361	0.6	520

Table 6.--Physical and chemical analyses of thermal and mineral water samples from the greater Yellowstone National Park area - continued
[mg/L, milligrams per liter; µg/L, micrograms per liter; --, not determined; <, less than]

Site Name	Alumi- nium, dis- solved (µg/L as Al)	Ammono- nium, dis- solved (mg/L as NH ₄)	Barium, dis- solved (mg/L as Ba)	Boron, dis- solved (mg/L as B)	Bromide, dis- solved (mg/L as Br)	Fluo- ride, dis- solved (mg/L as F)	Iron, dis- solved (mg/L as Fe)	Lithium, dis- solved (mg/L as Li)	Manga- nese, dis- solved (mg/L as Mn)	Nitrate, dis- solved (mg/L as NO ₃)	Phos- phate, dis- solved (mg/L as PO ₄)	Stron- tium, dis- solved (mg/L as Sr)	O-18/ O-16, stable isotope ratio (permil)	H-2/ H-1, stable isotope ratio (permil)	d-para- meter
<i>Sites inside Yellowstone National Park boundary</i>															
(M) Mammoth Area															
M-NG.1	5.6	0.61	0.066	3.76	0.51	2.3	0.21	1.59	0.028	0.03	0.06	1.84	-18.3	-146	0.7
M-NG.2	--	--	0.062	3.63	0.49	1.5	0.04	1.57	0.023	<0.1	<0.05	1.64	-18.1	-152	-7.6
M-NG.3	--	0.93	0.063	3.58	0.51	1.5	0.03	1.56	0.022	0.04	<0.05	1.63	-18.2	-145	0.5
M-OT	--	--	0.060	3.58	0.48	1.4	0.15	1.55	0.021	<0.02	0.12	1.58	-18.2	-149	-3.3
M-PP	--	0.22	0.049	3.51	0.50	2.0	<0.01	1.59	0.006	<0.02	<0.05	2.19	-17.2	-146	-8.6
M-PS	--	0.12	0.056	3.63	0.51	2.1	0.08	1.61	0.076	<0.02	<0.05	1.90	-17.8	-145	-3.0
M-SP.1	--	--	0.26	<0.05	<0.03	0.21	0.53	--	0.039	<0.02	<0.05	0.107	-18.4	-141	6.5
M-SP.2	--	--	0.26	0.02	<0.03	0.12	0.21	<0.002	0.025	<0.02	<0.05	0.110	-18.1	-138	6.5
M-Y10.1	3.9	1.0	0.055	4.17	0.54	2.3	2.1	--	0.037	0.03	<0.05	3.56	-18.4	-149	-2.1
M-Y10.2	--	--	0.055	4.00	0.54	1.7	0.75	1.69	0.040	<0.2	<0.05	3.49	-18.3	-148	-1.4
M-Y10.3	--	--	0.10	4.13	0.57	1.4	5.9	1.71	0.45	1.59	<0.05	3.44	-18.2	-150	-4.4
M-Y10.4	--	--	0.14	4.14	0.55	1.6	7.8	1.74	0.30	0.11	<0.05	3.74	-18.2	-149	-3.2
M-Y10.5	--	0.72	0.052	4.06	0.55	1.6	0.05	1.73	0.033	<0.02	<0.05	3.71	-17.9	-152	-8.8
(NM) Norris-Mammoth Corridor															
NM-AS1	--	8.1	0.064	0.12	<0.03	0.11	0.40	0.002	0.047	<0.02	<0.05	0.011	-11.7	-129	-35.9
NM-AS2	--	5.8	0.029	<0.05	<0.03	0.35	1.4	0.033	0.045	<0.02	<0.05	0.006	-12.3	-127	-28.4
NM-CW1	--	--	0.022	4.46	0.87	1.3	0.67	1.70	0.41	<0.1	<0.05	0.095	-17.1	-143	-6.7
NM-CW2	--	--	0.008	3.13	0.56	1.1	0.51	1.13	0.44	<0.1	<0.05	0.054	-17.7	-143	-1.8
NM-CW3.1	--	--	--	--	--	--	--	--	--	--	--	--	-16.8	-146	-11.9
NM-CW3.2	--	0.77	0.038	7.60	1.39	3.1	<0.01	4.17	0.037	0.02	<0.05	0.083	-15.7	-142	-16.4
NM-CW3.3	--	--	0.036	7.12	1.35	2.9	<0.01	4.01	0.037	<0.2	<0.05	0.073	-15.3	-143	-19.8
NM-CW3.4	--	0.52	0.028	6.68	1.28	3.1	<0.01	3.95	0.029	<0.02	<0.05	0.067	-15.0	-142	-21.3
NM-HB	--	1.8	0.079	5.15	0.49	0.7	0.09	0.74	0.38	<0.02	<0.05	2.15	-18.6	-150	-0.4
NM-S.1	--	--	0.22	2.37	0.32	2.2	<0.01	1.13	0.11	<0.02	<0.05	0.511	-18.8	-148	1.8
NM-S.2	--	--	--	--	--	--	--	--	--	--	--	--	-18.8	-150	-0.2
NM-W	--	18	0.077	<0.05	<0.03	<0.05	49.9	0.014	0.12	<0.02	<0.05	0.032	-5.3	-114	-71.2

Table 6.--Physical and chemical analyses of thermal and mineral water samples from the greater Yellowstone National Park area - continued

Site Name	Field Sample ID	Date	Temperature, water (Deg C)	Specific conductance (µS/cm)	pH (stand-ard units)	Silica, dissolved (mg/L as SiO ₂)	Calcium, dissolved (mg/L as Ca)	Magne-sium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potas-sium, dissolved (mg/L as K)	Alka-linity, lab (mg/L as HCO ₃)	Sulfate, dissolved (mg/L as SO ₄)	Chlo-ride, dissolved (mg/L as Cl)	Solids, sum of consti-tuents, dissolved (mg/L)
<u>(N) Norris Basin</u>														
N-C	90YNP-114	06-15-90	83	1800	6.29	535	3.62	0.08	313	62.4	38	70.6	511	1586
N-G	90YNP-117	06-15-90	87	2400	6.8	602	2.42	0.01	394	103	32	41.2	695	1943
N-PG.1	89YNP-109	06-22-89	>86	2340	8.5	741	3.49	0.06	388	91.1	62	23.2	687	2066
N-PG.2	90YNP-116	06-15-90	87	2350	8.0	504	3.39	0.02	400	92.7	55	24.0	700	1850
N-NP	89YNP-108	06-22-89	--	2140	--	369	3.84	0.15	348	75.3	--	81.3	595	1536
<u>Calcite Springs thermal Area (near Tower Junction)</u>														
YP-C1.1	89YNP-252	06-24-89	94	1670	7.5	191	31.5	13.0	197	95.0	200	250	238	1408
YP-C1.2	90YNP-111	06-14-90	94	1610	7.35	166	35.8	12.8	199	92.7	198	264	233	1414
YP-C1.3	90YNP-115	06-15-90	--	1380	--	172	29.7	5.10	202	86.5	142	258	240	1362
YP-C2	90YNP-110	06-14-90	94	1680	--	158	41.3	10.2	202	97.0	134	333	239	1427
<u>Rainbow Springs thermal area (Wrong Creek- southwest side of Mirror Plateau)</u>														
YP-R2	89YNP-260	06-27-89	76.1	1650	6.68	337	26.4	15.3	270	51.3	506	153	198	1671
YP-R33	90YNP-133	06-18-90	81	1700	--	315	22.0	9.03	285	62.2	381	281	170	1639
YP-R4	90YNP-132	06-18-90	78	1660	--	323	27.9	17.2	275	51.2	501	154	199	1664
YP-ROS	90YNP-134	06-18-90	30	435	--	46.2	6.29	4.37	34.3	7.43	59	24.7	64.0	283
<u>Washburn Hot Springs thermal area (Washburn Range - between Mt. Washburn and Grand Canyon of Yellowstone)</u>														
YP-W1	90YNP-112	06-14-90	80	3490	--	58.7	3.97	0.23	1.0	1.58	216	1200	0.8	2064
YP-W2	90YNP-113	06-14-90	--	4300	3.15	280	18.8	9.07	14.5	4.44	--	1790	0.9	2741
<u>Thermal waters- Outside Yellowstone National Park</u>														
<u>(CS) Corwin Springs Known Geothermal Resources Area</u>														
CS-BC1	89YNP-105	06-21-89	31.6	2880	5.8	34.9	507	91.4	113	48.8	1240	869	42.8	2961
CS-BC2.1	89YNP-308	09-11-89	32	2650	6.08	32.7	477	89.7	112	47.3	1250	824	42.4	2888
CS-BC2.2	90YNP-105	06-12-90	32	2920	6.15	35.2	503	98.4	121	50.0	1240	878	42.7	2986
CS-BC3	89YNP-309	09-11-89	14	4290	7.34	24.0	10.0	2.57	1220	5.52	3260	14.1	43.4	4590
CS-BCG	91YNP-124	09-04-91	29	2930	--	--	--	--	--	47.4	--	907	40.2	--
CS-LD.1	89YNP-110	06-23-89	68	2580	6.46	56.7	333	64.1	240	24.5	295	1250	44.8	2318
CS-LD.2	89YNP-307	09-09-89	--	2570	7.5	51.6	328	59.6	236	23.7	289	1250	43.9	2297

Table 6.--Physical and chemical analyses of thermal and mineral water samples from the greater Yellowstone National Park area - continued

Site Name	Alumi- nium, dis- solved (µg/L as Al)	Ammono- nium, dis- solved (mg/L as NH ₄)	Barium, dis- solved (mg/L as Ba)	Boron, dis- solved (mg/L as B)	Bromide, dis- solved (mg/L as Br)	Fluo- ride, dis- solved (mg/L as F)	Iron, dis- solved (mg/L as Fe)	Lithium, dis- solved (mg/L as Li)	Manga- nese, dis- solved (mg/L as Mn)	Nitrate, dis- solved (mg/L as NO ₃)	Phos- phate, dis- solved (mg/L as PO ₄)	Stron- tium, dis- solved (mg/L as Sr)	O-18/ O-16, stable isotope ratio (permil)	H-2/ H-1, stable isotope ratio (permil)	d-para- meter
(N) Norris Basin															
N-C	--	0.80	0.013	7.25	1.49	4.9	0.04	4.61	0.018	<0.02	<0.05	0.017	-19.4	-145	10.2
N-G	--	0.67	0.009	9.92	2.07	5.9	<0.01	6.74	0.003	0.04	<0.05	0.012	-13.5	-140	-32.0
N-PG.1	--	0.14	0.004	9.89	2.12	5.8	0.02	6.55	0.004	0.03	<0.05	0.017	-15.7	-144	-18.2
N-PG.2	--	0.18	0.009	9.85	2.07	6.2	<0.01	6.72	<0.002	<0.02	<0.05	0.014	-14.8	-143	-24.1
N-NP	--	0.84	0.051	8.58	1.84	4.8	1.2	5.65	0.057	0.03	<0.05	0.016	-14.7	-140	-22.0
Calcite Springs thermal Area (near Tower Junction)															
YP-C1.1	--	--	0.16	32.4	0.90	3.9	0.12	2.17	0.036	0.07	<0.05	1.36	-14.4	-146	-30.6
YP-C1.2	--	28	0.11	31.2	0.87	3.2	0.25	2.11	0.053	0.09	<0.05	1.11	-14.4	-146	-31.1
YP-C1.3	--	28	0.050	32.4	0.96	3.5	0.04	2.11	0.032	0.06	<0.05	0.447	-13.7	-146	-36.8
YP-C2	--	26	0.12	31.4	0.90	2.9	0.04	2.22	0.028	0.04	<0.05	1.38	-14.1	-145	-32.8
Rainbow Springs thermal area (Wrong Creek- southwest side of Mirror Plateau)															
YP-R2	--	--	0.13	19.2	0.59	2.8	0.20	0.52	0.094	0.03	0.04	0.196	-16.2	-147	-16.9
YP-R33	--	11	0.086	17.3	0.53	1.6	<0.01	0.62	0.19	<0.02	<0.05	0.124	-15.6	-142	-17.1
YP-R4	--	8.4	0.13	18.2	0.60	1.8	0.19	0.52	0.099	0.03	<0.05	0.195	-14.9	-143	-24.3
YP-ROS	--	2.1	0.040	2.64	0.10	0.38	3.0	0.069	0.15	0.04	<0.05	22.0	-14.8	-125	-6.9
Washburn Hot Springs thermal area (Washburn Range - between Mt. Washburn and Grand Canyon of Yellowstone)															
YP-W1	--	567	0.035	0.20	<0.03	<0.05	0.01	0.008	0.006	0.2	<0.25	0.125	-3.3	-118	-91.8
YP-W2	--	560	0.011	6.87	<0.03	<0.05	21.5	<0.002	0.29	<0.02	<0.25	0.060	-6.8	-116	-61.1
<i>Thermal waters- Outside Yellowstone National Park</i>															
(CS) Corwin Springs Known Geothermal Resources Area															
CS-BC1	--	--	0.029	1.05	0.13	2.5	1.2	0.42	0.064	0.02	<0.05	3.55	-19.4	-146	9.6
CS-BC2.1	--	--	0.029	1.09	0.13	1.4	0.06	0.39	0.065	<0.02	<0.05	3.23	-19.4	-148	7.7
CS-BC2.2	--	0.27	0.029	1.30	0.14	1.5	1.2	0.43	0.071	<0.02	<0.05	3.49	-19.5	-148	8.1
CS-BC3	--	--	1.2	1.13	0.34	2.2	<0.01	1.16	0.064	0.26	<0.05	1.26	-18.8	-146	5.1
CS-BCG	--	--	--	--	0.13	3.2	--	0.43	--	<0.02	<0.05	--	-19.4	-148	6.8
CS-LD.1	0.43	0.19	0.035	0.46	0.21	3.5	0.05	0.28	0.021	0.08	<0.05	4.22	-19.3	-144	10.7
CS-LD.2	--	--	0.035	0.58	0.20	3.5	0.21	0.27	0.021	<0.2	<0.05	4.15	-19.4	-146	9.6

Table 6.--Physical and chemical analyses of thermal and mineral water samples from the greater Yellowstone National Park area - continued

Site Name	Field Sample ID	Date	Temperature, water (Deg C)	Specific conductance (µS/cm)	pH (stand-ard units)	Silica, dissolved (mg/L as SiO ₂)	Calcium, dissolved (mg/L as Ca)	Magne-sium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potas-sium, dissolved (mg/L as K)	Alka-linity, lab (mg/L as HCO ₃)	Sulfate, dissolved (mg/L as SO ₄)	Chlo-ride, dissolved (mg/L as Cl)	Solids, sum of consti-tuents, dissolved (mg/L)
CS-LD.3	90YNP-109	06-12-90	--	--	--	--	--	--	--	--	--	--	--	--
CS-LD.4	92YNP-2	07-11-92	--	2570	--	--	--	--	--	--	--	--	--	--
CS-MS	89YNP-27	05-21-89	--	--	--	--	--	--	--	--	--	--	--	--
CS-NL	89YNP-112	06-23-89	58	2490	6.37	73.6	331	60.8	236	25.2	345	1170	43.2	2291
CS-MW.1	89YNP-30	05-21-89	--	--	--	--	--	--	--	--	--	--	--	--
CS-MW.2	89YNP-114	06-23-89	23.5	2300	7.68	64.3	97.1	92.2	307	28.7	274	1000	36.1	1909
CS-MW.3	89YNP-305	09-09-89	--	2290	7.8	60.2	95.5	89.6	311	28.2	265	990	35.2	1882
CS-CUT1	89YNP-113	06-23-89	54.1	2440	6.67	76.1	334	73.2	210	25.7	243	1230	37.5	2238
(AN) Absaroka Range - northern area														
AN-C.1	89YNP-115	06-24-89	44	383	7.52	38.1	34.5	8.19	35.4	6.78	173	43.8	10.1	352
AN-C.2	90YNP-121	06-16-90	--	409	--	36.8	35.3	8.76	36.0	7.32	177	46.6	10.9	361
(MR) Madison Range														
MR-WC	89YNP-207	06-22-89	64	473	8.62	54.9	6.86	1.16	101	2.06	164	42.3	19.2	410

Table 6.--Physical and chemical analyses of thermal and mineral water samples from the greater Yellowstone National Park area - continued

Site Name	Alumi- nium, dis- solved (µg/L as Al)	Ammono- nium, dis- solved (mg/L as NH ₄)	Barium, dis- solved (mg/L as Ba)	Boron, dis- solved (mg/L as B)	Bromide, dis- solved (mg/L as Br)	Fluo- ride, dis- solved (mg/L as F)	Iron, dis- solved (mg/L as Fe)	Lithium, dis- solved (mg/L as Li)	Manga- nese, dis- solved (mg/L as Mn)	Nitrate, dis- solved (mg/L as NO ₃)	Phos- phate, dis- solved (mg/L as PO ₄)	Stron- tium, dis- solved (mg/L as Sr)	O-18/ O-16, stable isotope ratio (permil)	H-2/ H-1, stable isotope ratio (permil)	d-pa- ra- meter
CS-LD.3	--	--	--	--	--	--	--	--	--	--	--	--	-19.0	-145	6.2
CS-LD.4	--	--	--	--	--	--	--	--	--	--	--	--	-19.3	-146	8.2
CS-MS	--	--	--	--	--	--	--	--	--	--	--	--	-19.5	-148	8.6
CS-NL	--	0.13	0.046	0.46	0.20	3.0	0.03	0.28	0.064	0.42	<0.05	4.22	-19.2	-146	8.0
CS-MW.1	--	--	--	--	--	--	--	--	--	--	--	--	-18.8	-146	4.9
CS-MW.2	0.79	0.71	0.019	0.63	0.19	1.9	0.32	0.12	0.21	<0.02	<0.05	1.63	-19.5	-147	8.7
CS-MW.3	--	--	0.018	0.61	0.16	1.5	0.36	0.12	0.19	<0.02	<0.05	1.55	-19.4	-147	8.1
CS-CUT1	0.55	0.23	0.029	0.54	0.19	2.8	0.75	0.21	0.16	0.02	<0.05	4.48	-19.4	-145	10.2
(AN) Absaroka Range - northern area															
AN-C.1	--	0.10	0.10	0.05	0.04	0.9	<0.01	0.028	0.002	0.64	<0.05	0.383	-19.3	-147	6.9
AN-C.2	--	0.12	0.11	0.08	0.06	0.97	<0.01	0.031	0.008	0.74	<0.05	0.373	-19.0	-148	4.2
(MR) Madison Range															
MR-WC	--	--	0.017	<0.05	0.09	17.7	<0.01	0.067	<0.002	0.28	<0.05	0.041	-20.2	-146	15.4

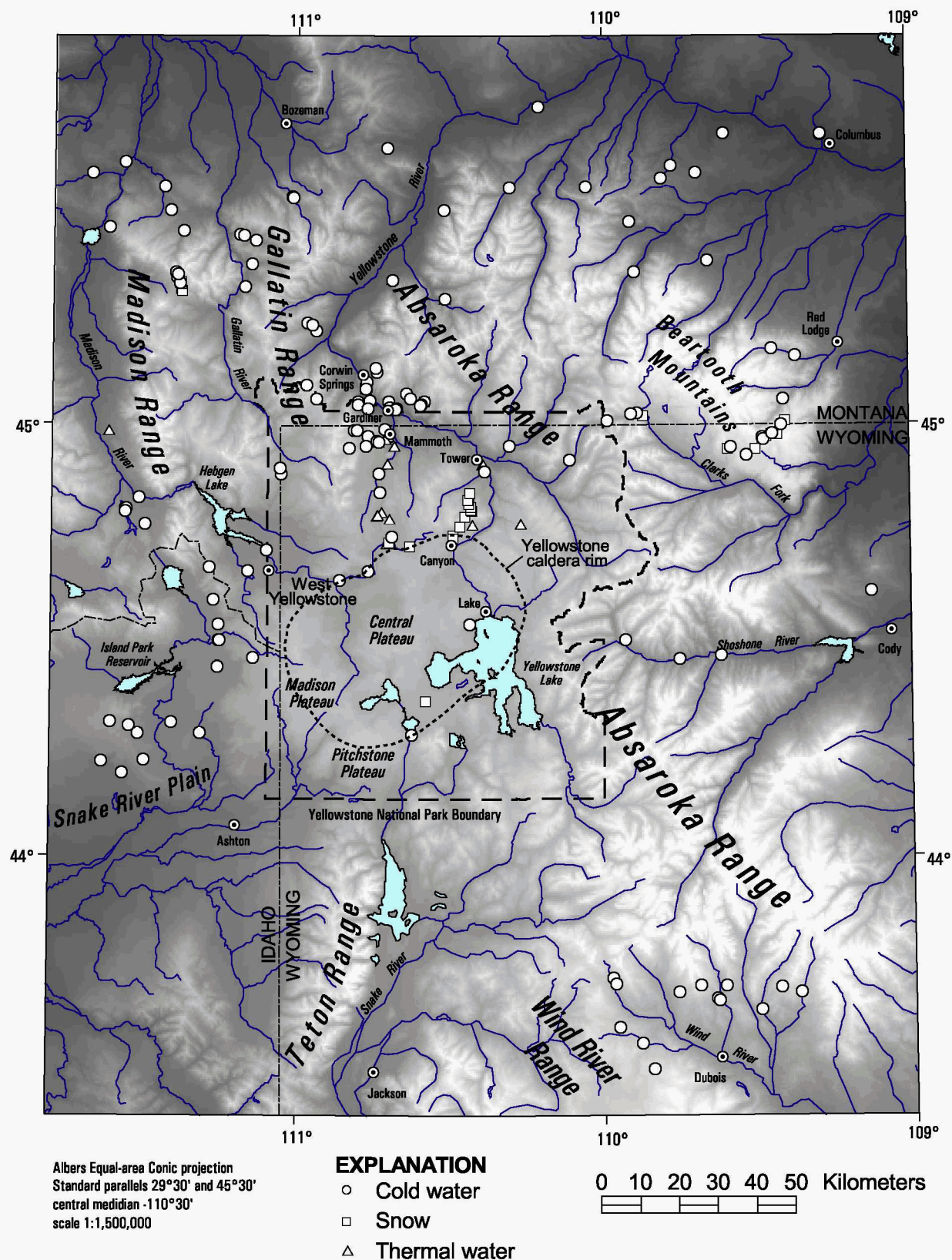


Figure 1. Location of sampling sites for cold water, snow, and thermal water, in the greater Yellowstone National Park area.

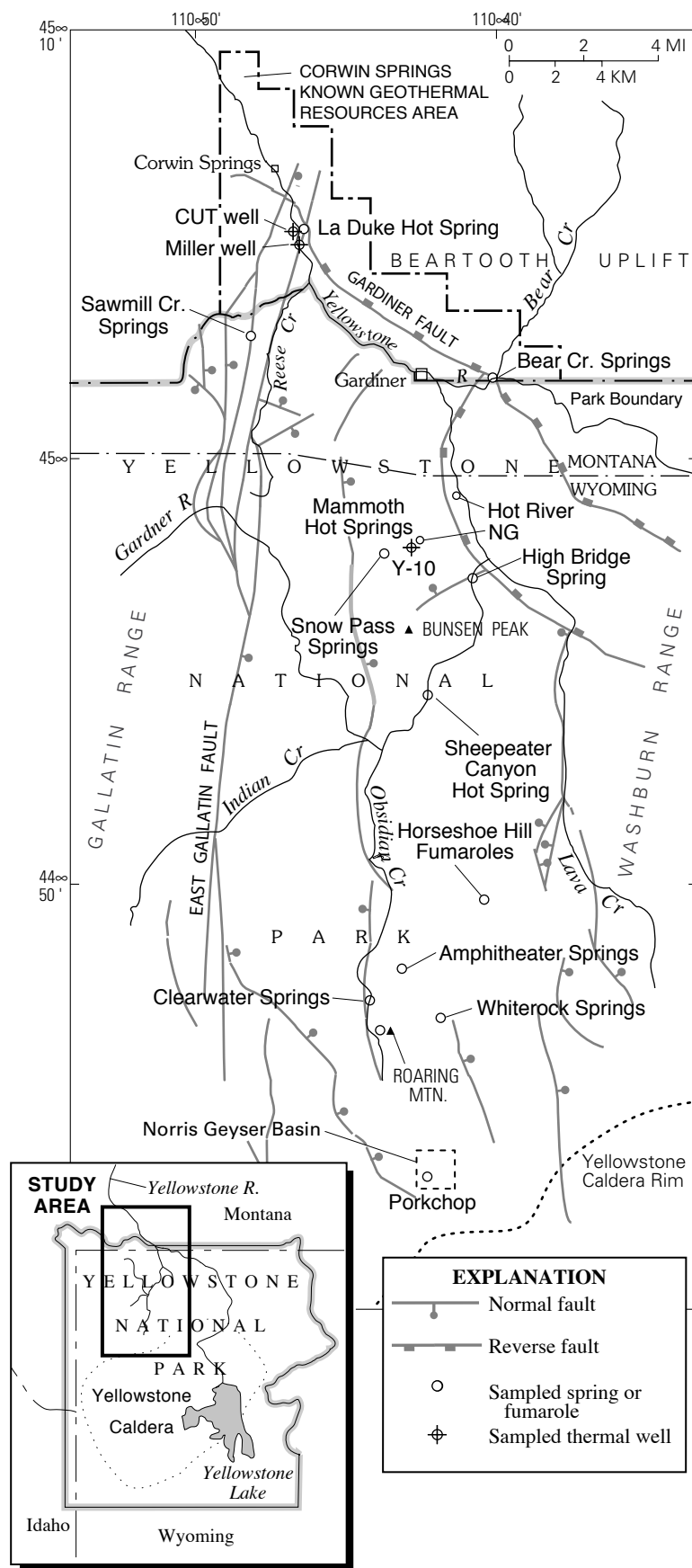


Figure 2. Regional setting for the Norris-Mammoth corridor that extends from Yellowstone caldera through Mammoth Hot Springs to Corwin Springs Known Geothermal Resources Area. The thermal springs, including Narrow Gauge spring (NG) and wells, including Y-10 sampled are indicated (modified from Kharaka and others, 1991).

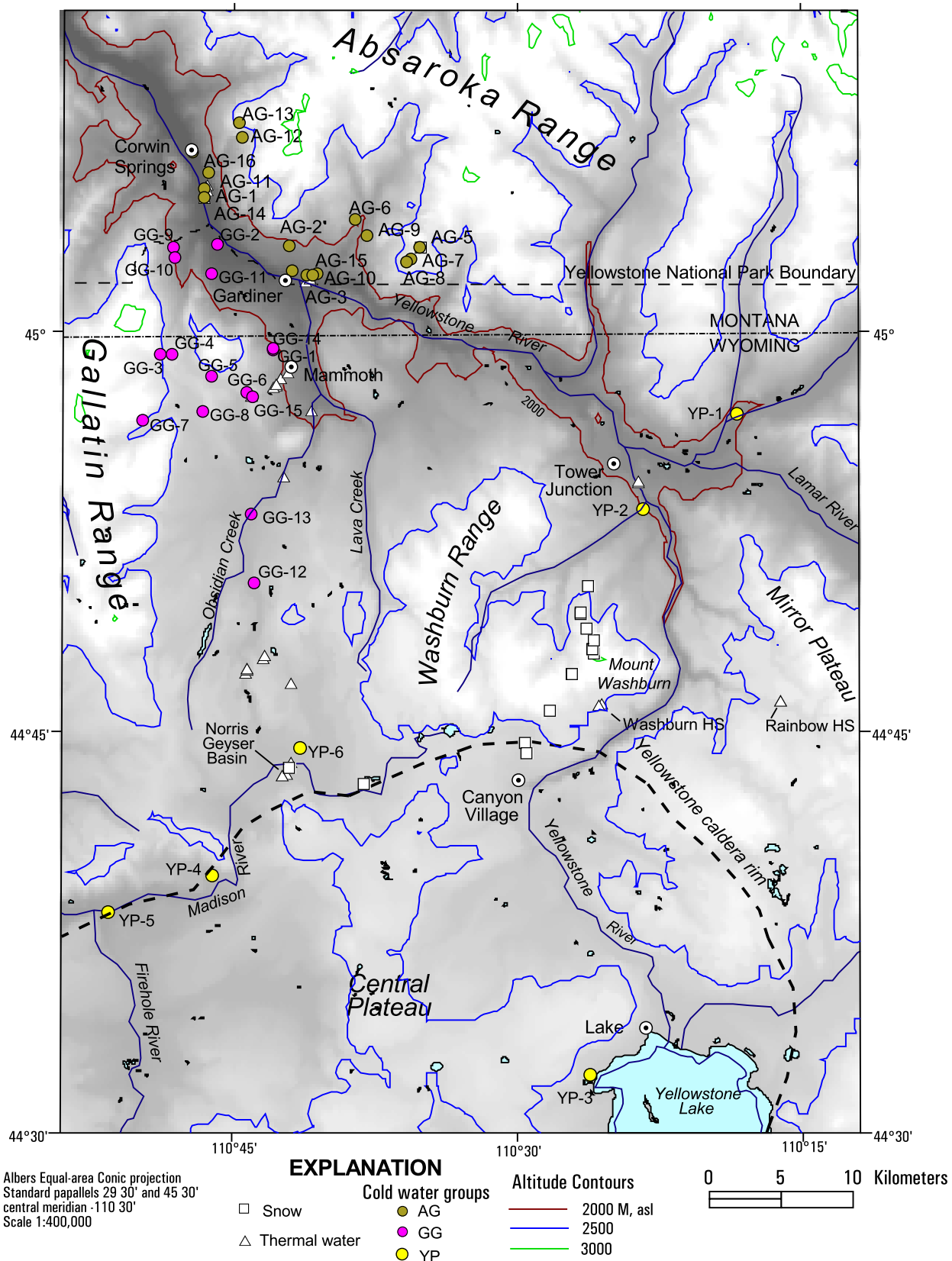


Figure 3. Location of sampling sites for cold water (groups AG, GG, and YP), snow and thermal water in the Gardiner-Mammoth area and northern portion of Yellowstone National Park.

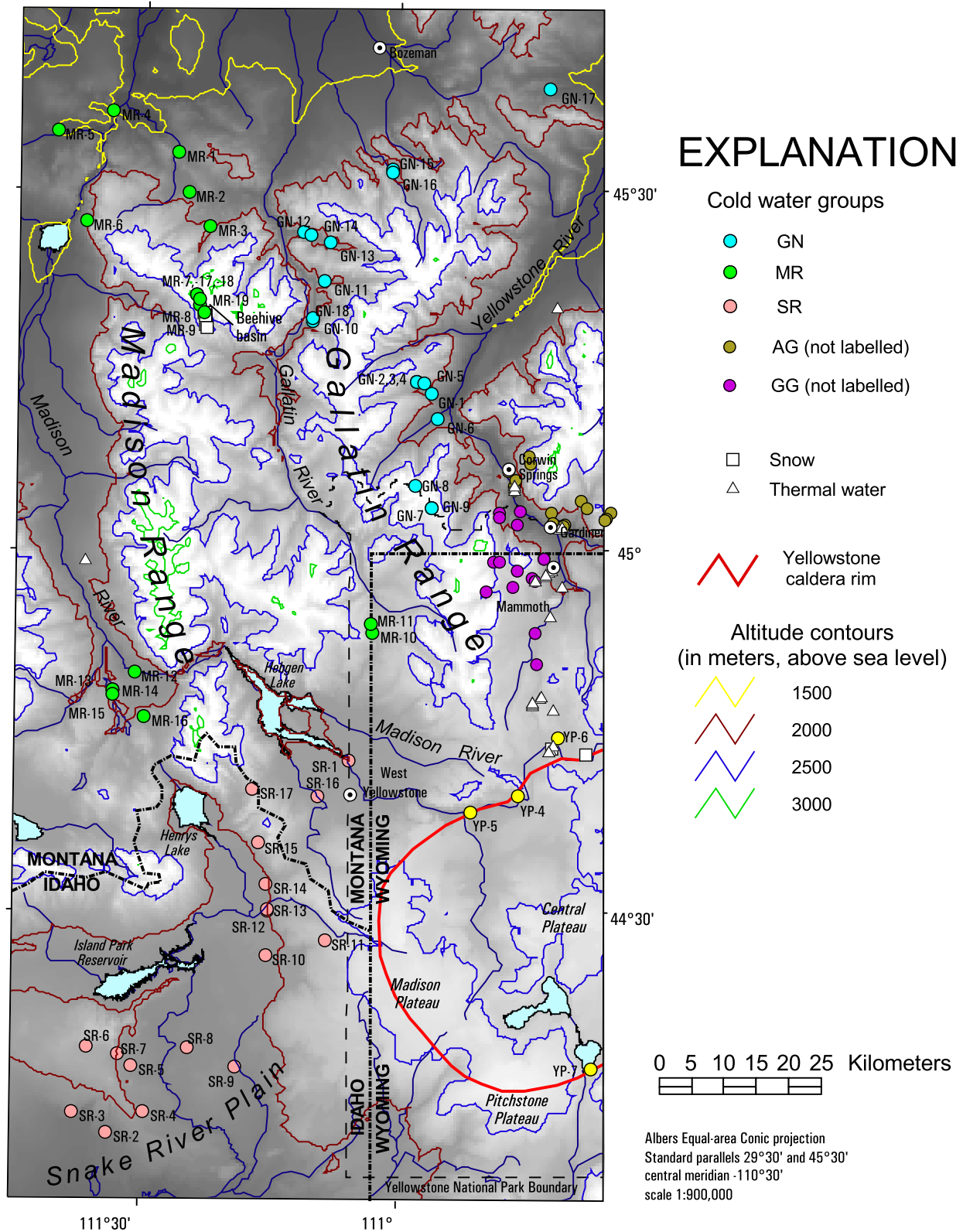
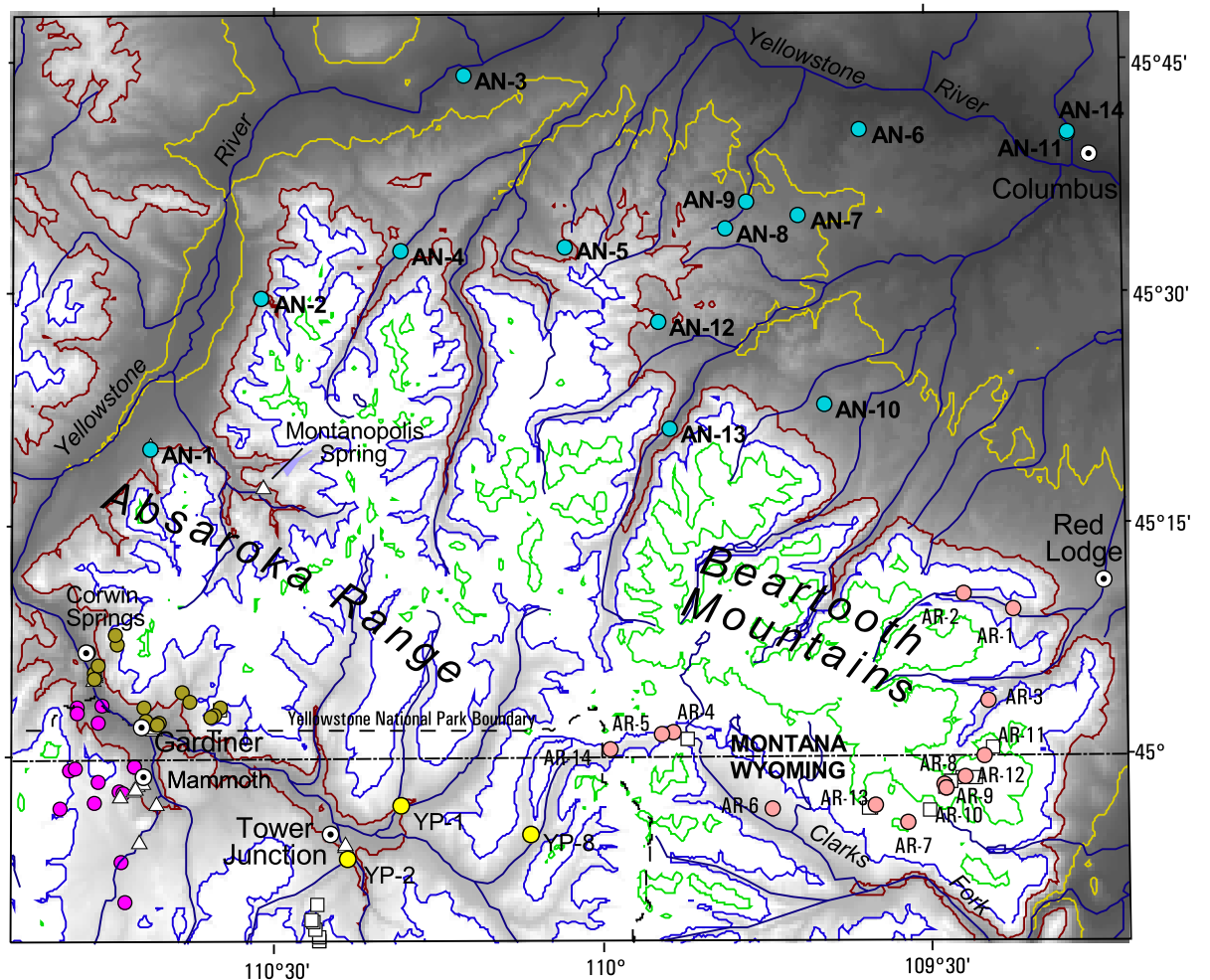


Figure 4. Location of sampling sites for cold water (groups GN, MR, SR, and YP), snow, and thermal water in the western portion of the study area (Gallatin Range, Madison Range, Snake River Plain and Yellowstone volcanic plateaus).



Albers Equal-area Conic projection
Standard parallels 29°30' and 45°30'
central meridian -110°30'
scale 1:900,000

EXPLANATION

Cold water groups

- AN
- AR
- YP
- AG (not labelled)
- GG (not labelled)

□ Snow

△ Thermal water

Altitude contours (in M, asl)

- 1500
- 2000
- 2500
- 3000

0 5 10 15 20 25 Kilometers

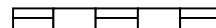
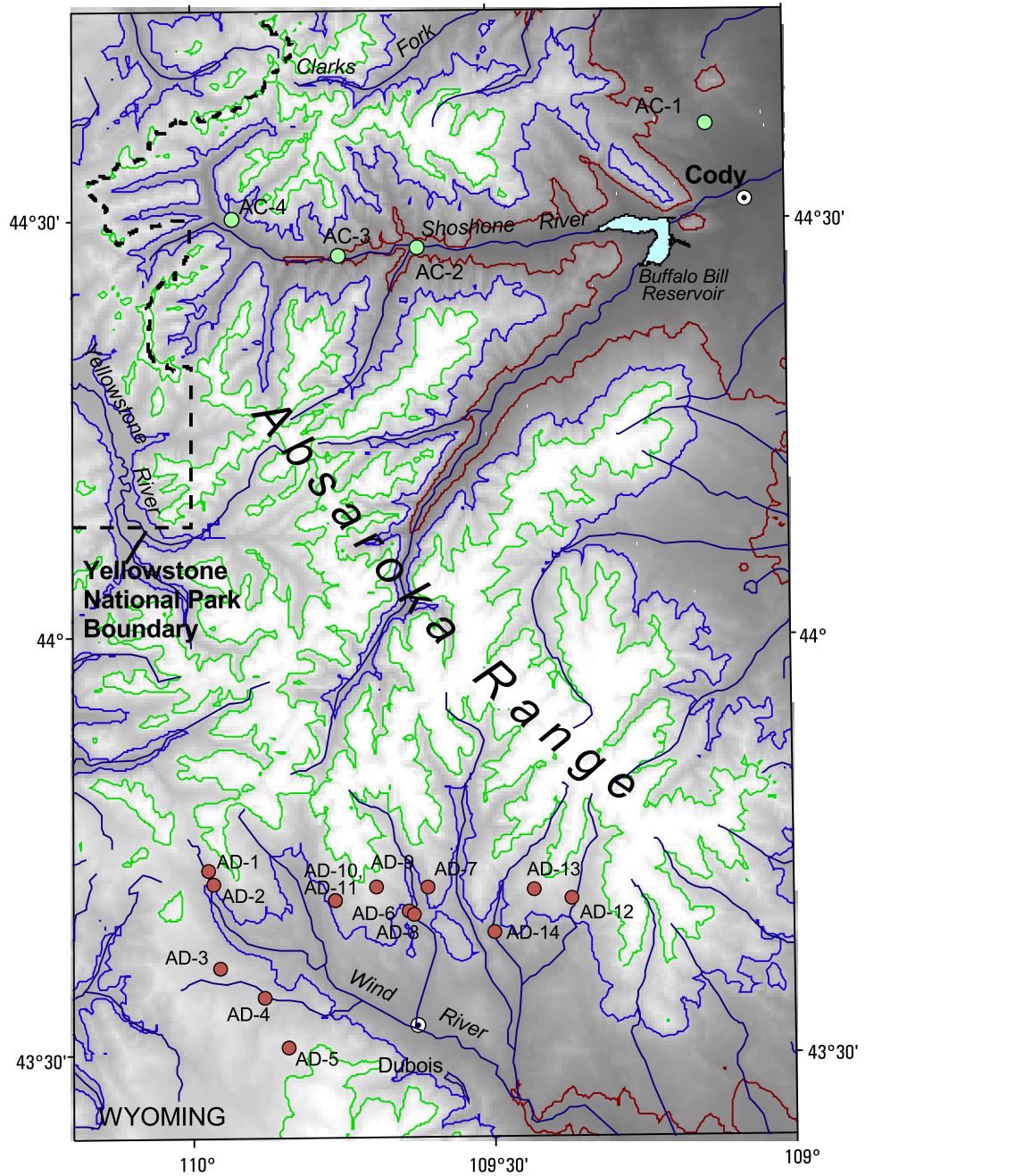


Figure 5. Location of sampling sites for cold water (groups AN, AR, and YP), snow, and thermal water in the northeast portion of the study area.



Albers Equal-area Conic projection
 Standard parallels 29°30' and 45°0'
 central meridian -110°30'
 scale 1:900,000

0 6 12 18 24 30 Kilometers

Figure 6. Location of sampling sites for cold water groups AC and AD, in the southeast portion of the study area.

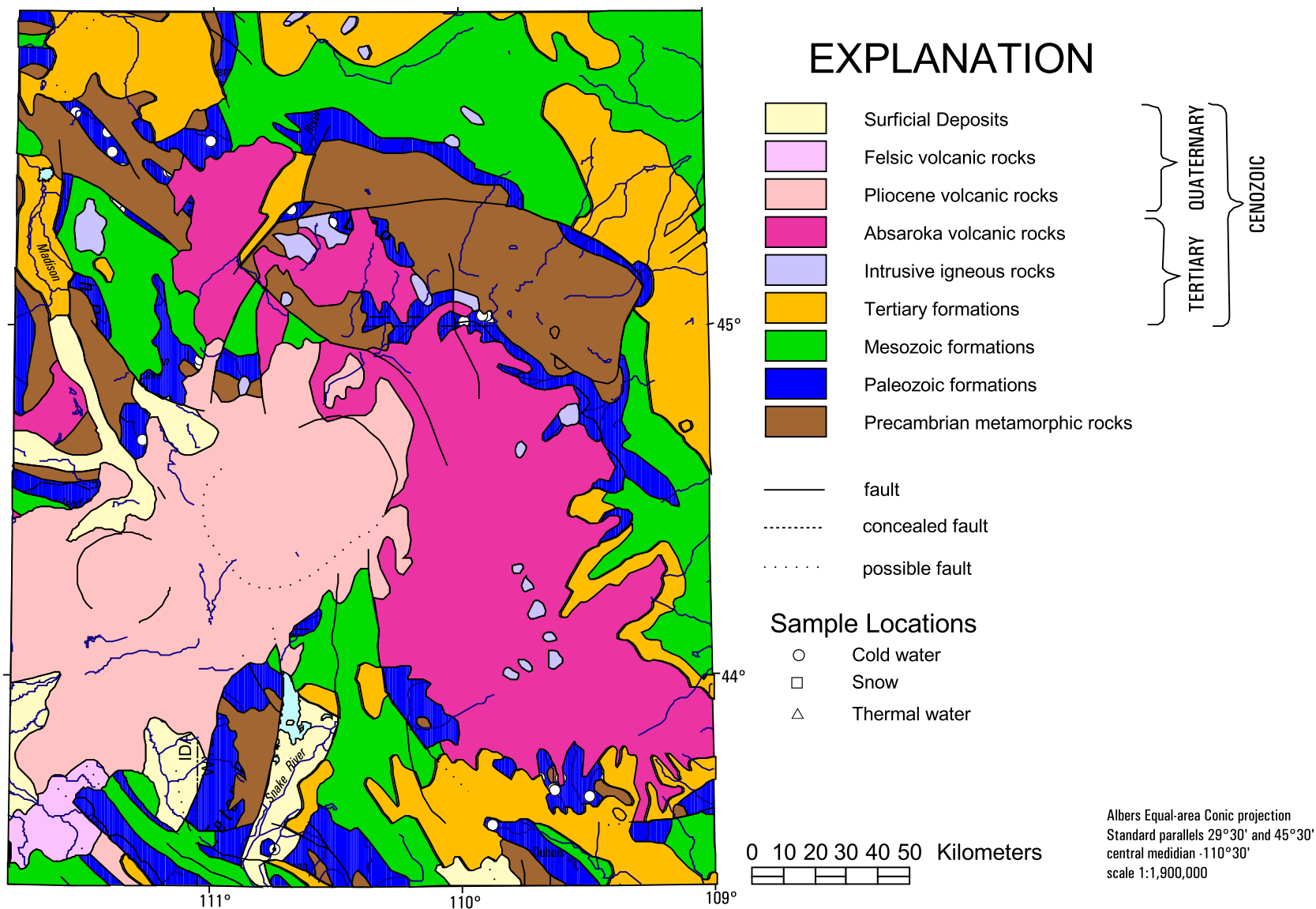


Figure 7. Generalized geologic map of the greater Yellowstone National Park area. Modified from digital representation of the 1974 King-Bickman map by Schruben et al.(1997).

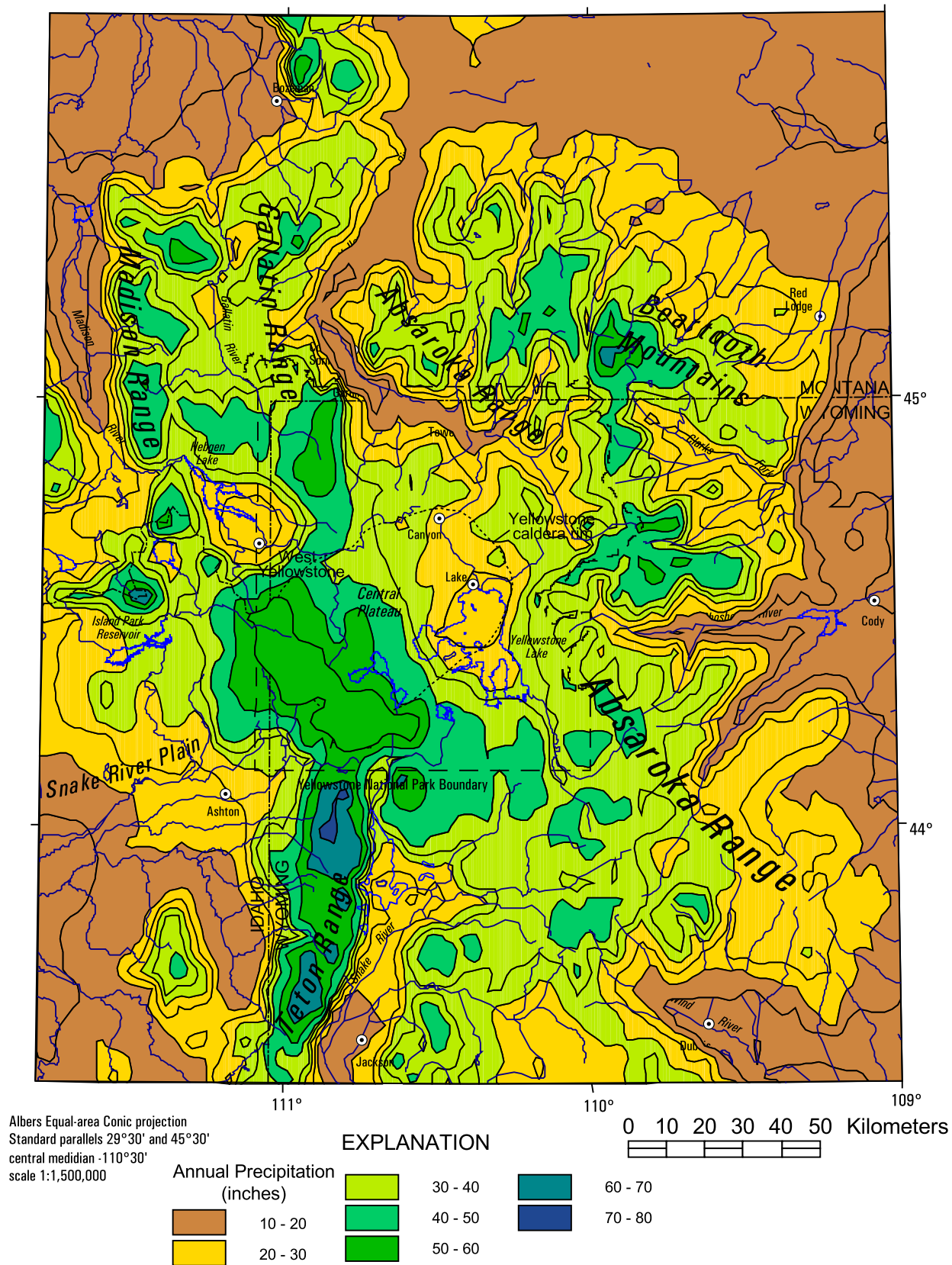


Figure 8. Mean annual precipitation for the greater Yellowstone National Park area (National Atlas, 2002).

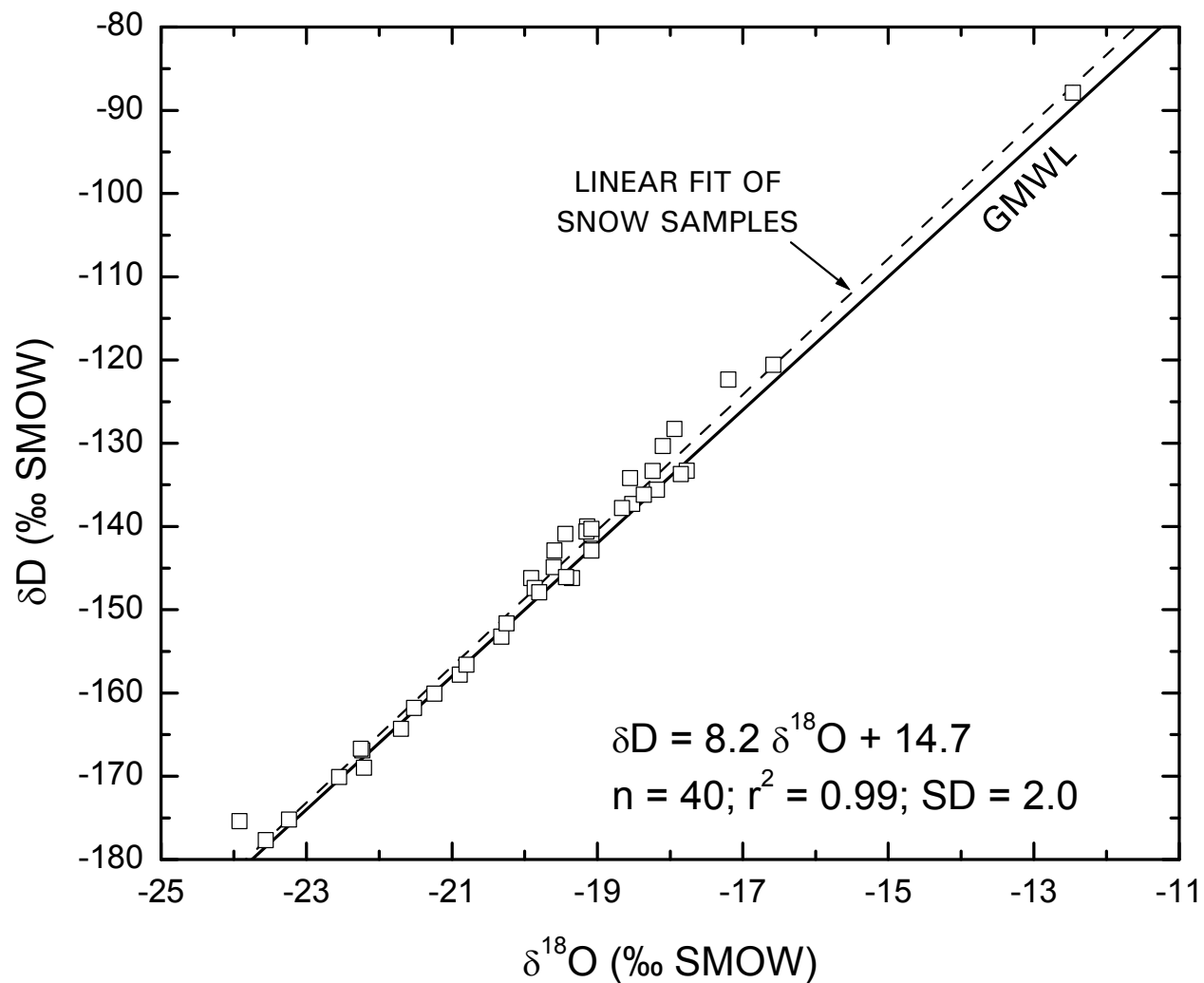


Figure 9. The stable isotope composition of 40 snow samples collected from the study area and their resultant Local Meteoric Water Line (LMWL) of $\delta\text{D} = 8.2 \delta^{18}\text{O} + 14.7$, which approximates the GMWL.

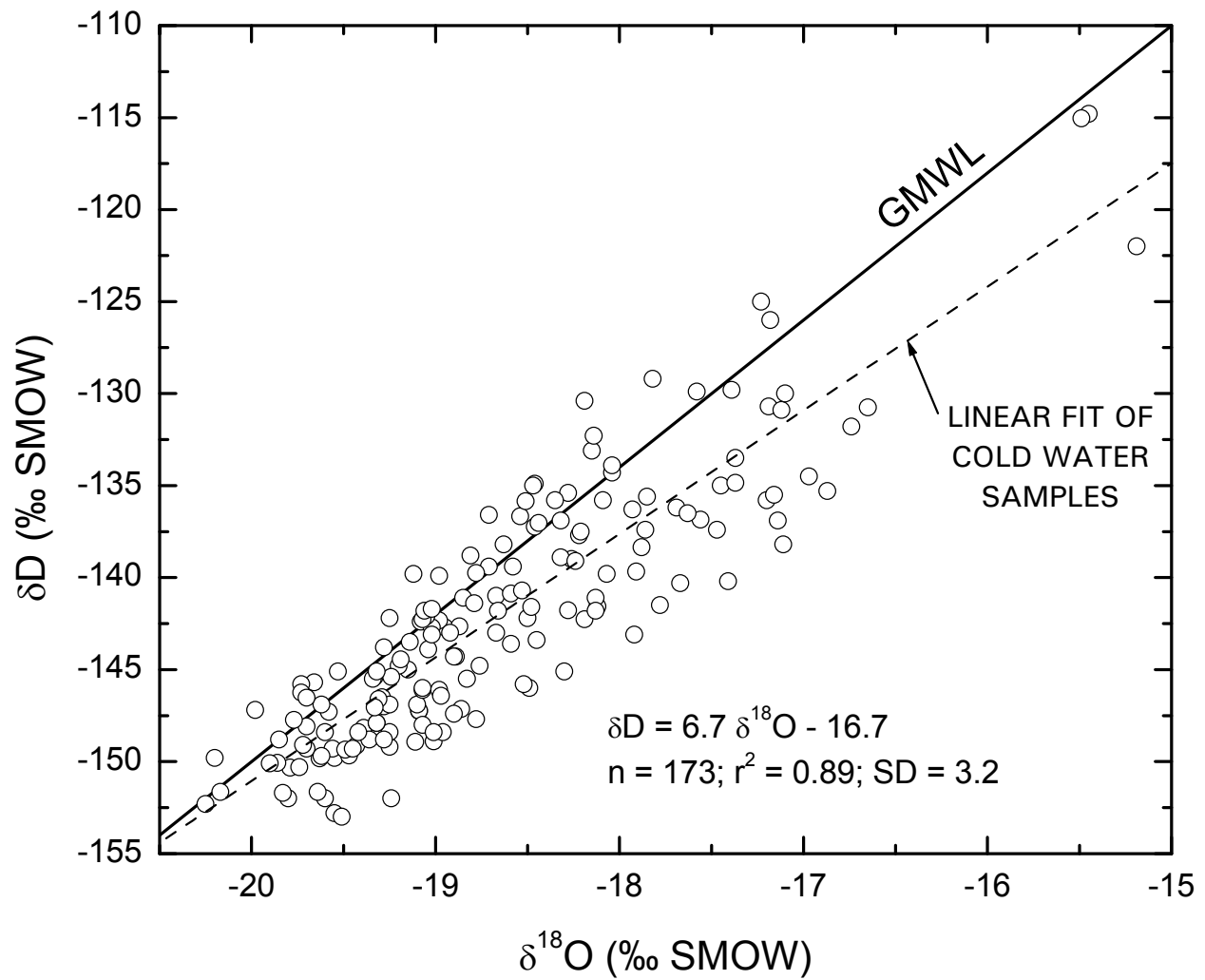


Figure 10. The stable isotope composition of cold-water samples collected in the study area. Note the departure of the linear fit from the GMWL, especially in samples with heavy isotopes.

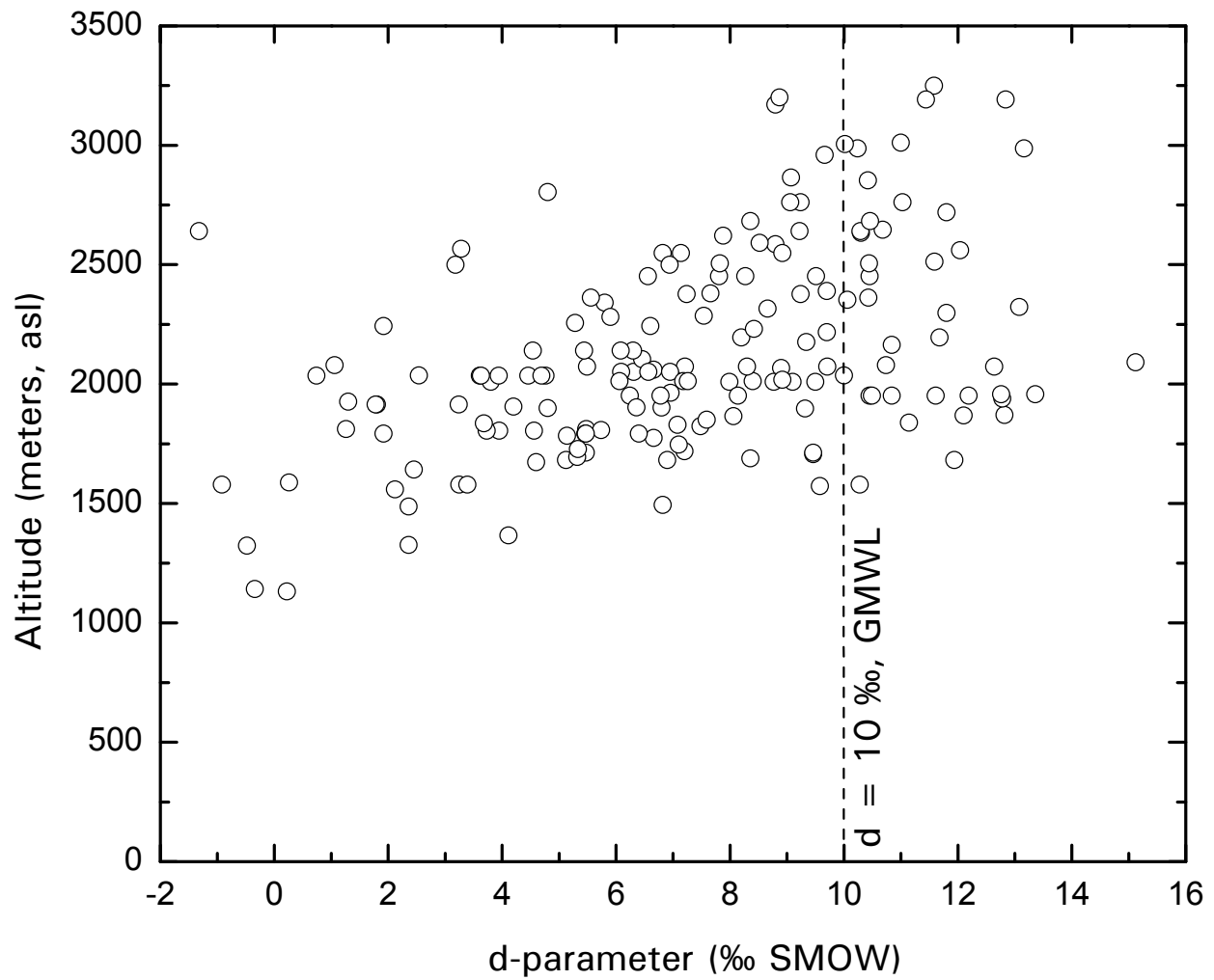


Figure 11. Variation of d -parameter (see text) with altitude for the cold water samples. Note that the samples with d -parameter values <5 , indicating significant evaporation, are mainly from low altitude areas.

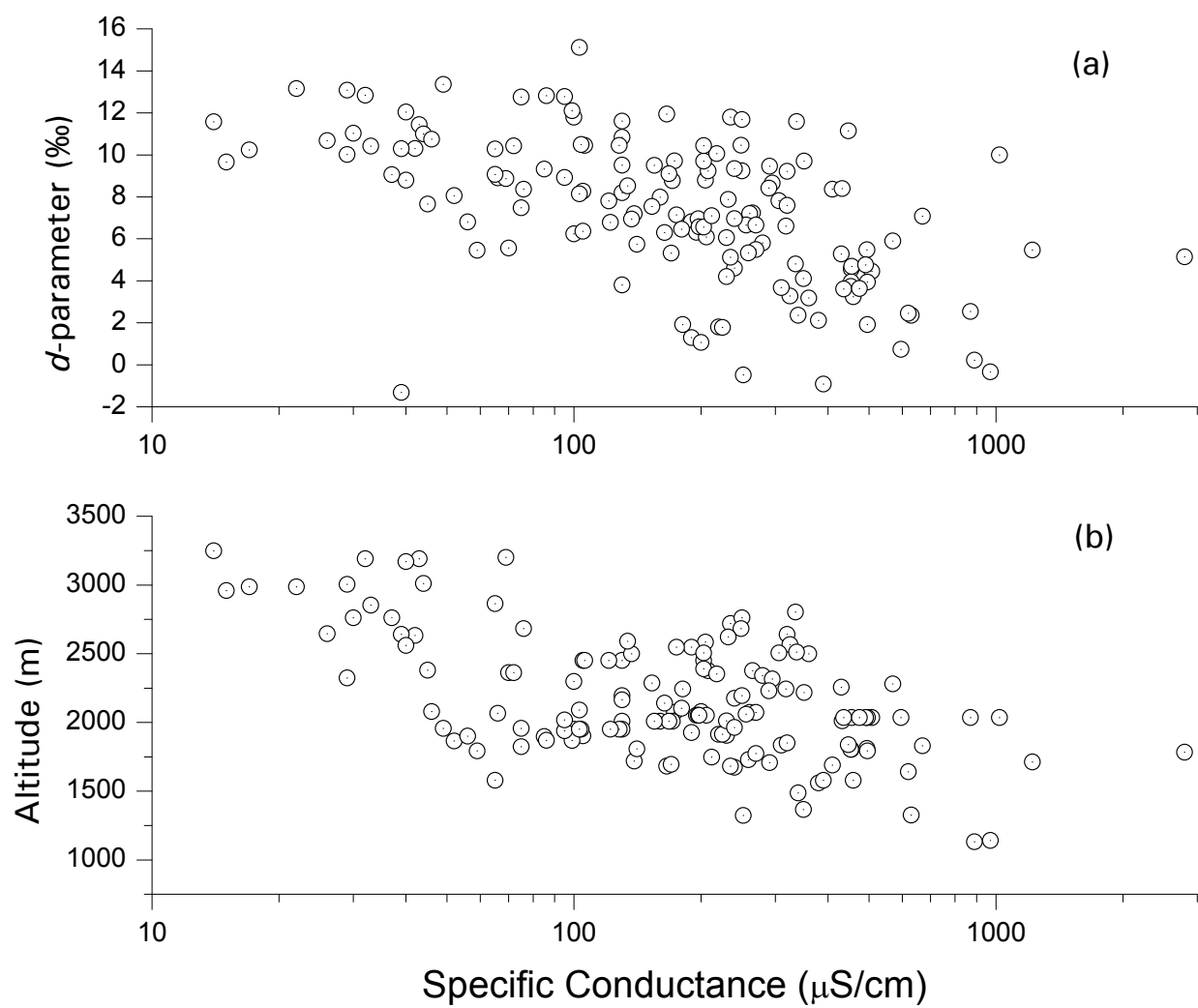


Figure 12. Scatter plot of d -parameter (a) and altitude (b) vs. specific conductance (log scale) for cold water samples.

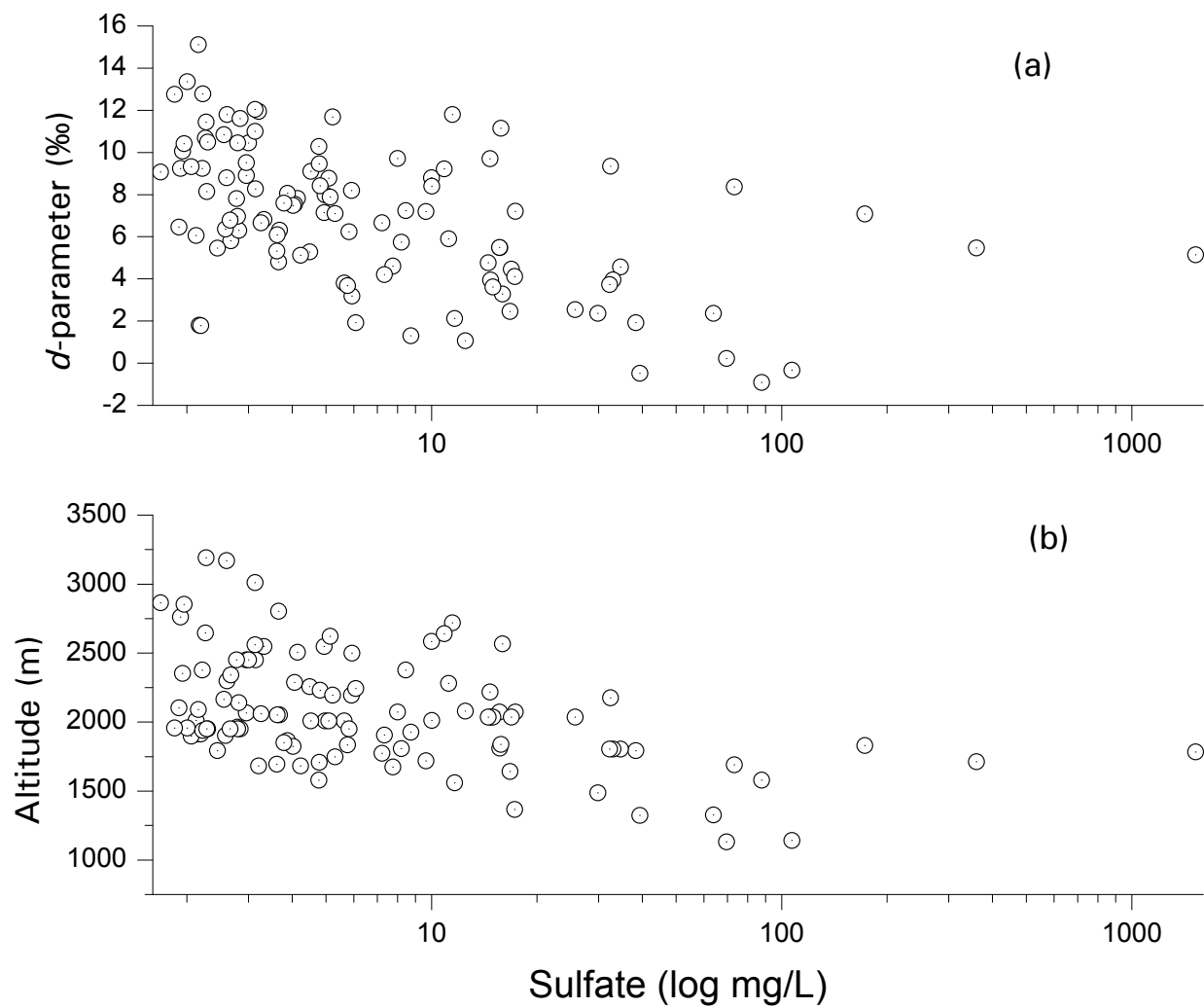


Figure 13. Scatter plot of *d*-parameter (a) and altitude (b) vs sulfate concentrations (log scale) for cold water samples.

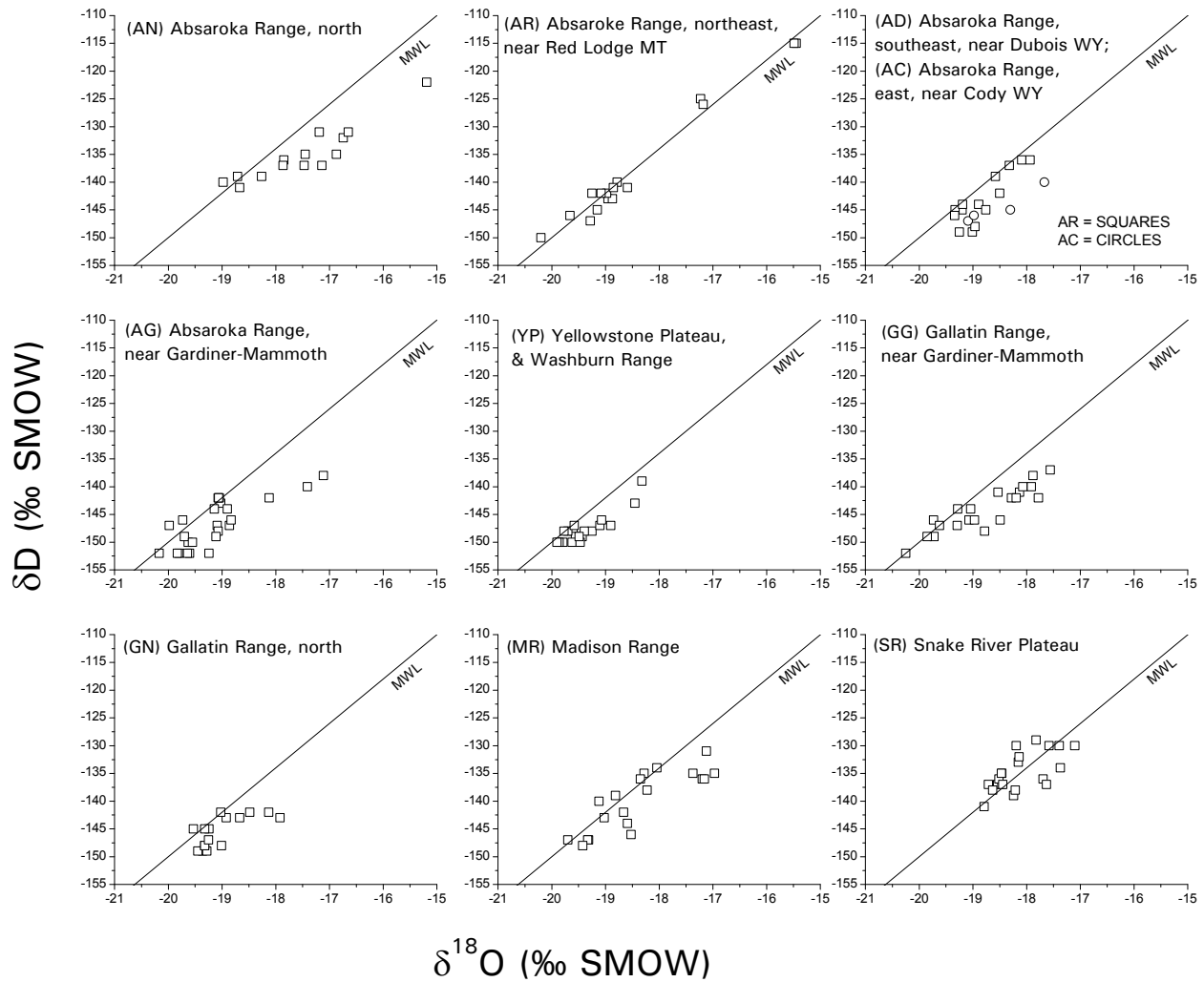


Figure 14. The stable isotope composition for cold-water samples obtained from the nine (AD and AC samples are plotted together in top right) from geographic/physiographic regions.

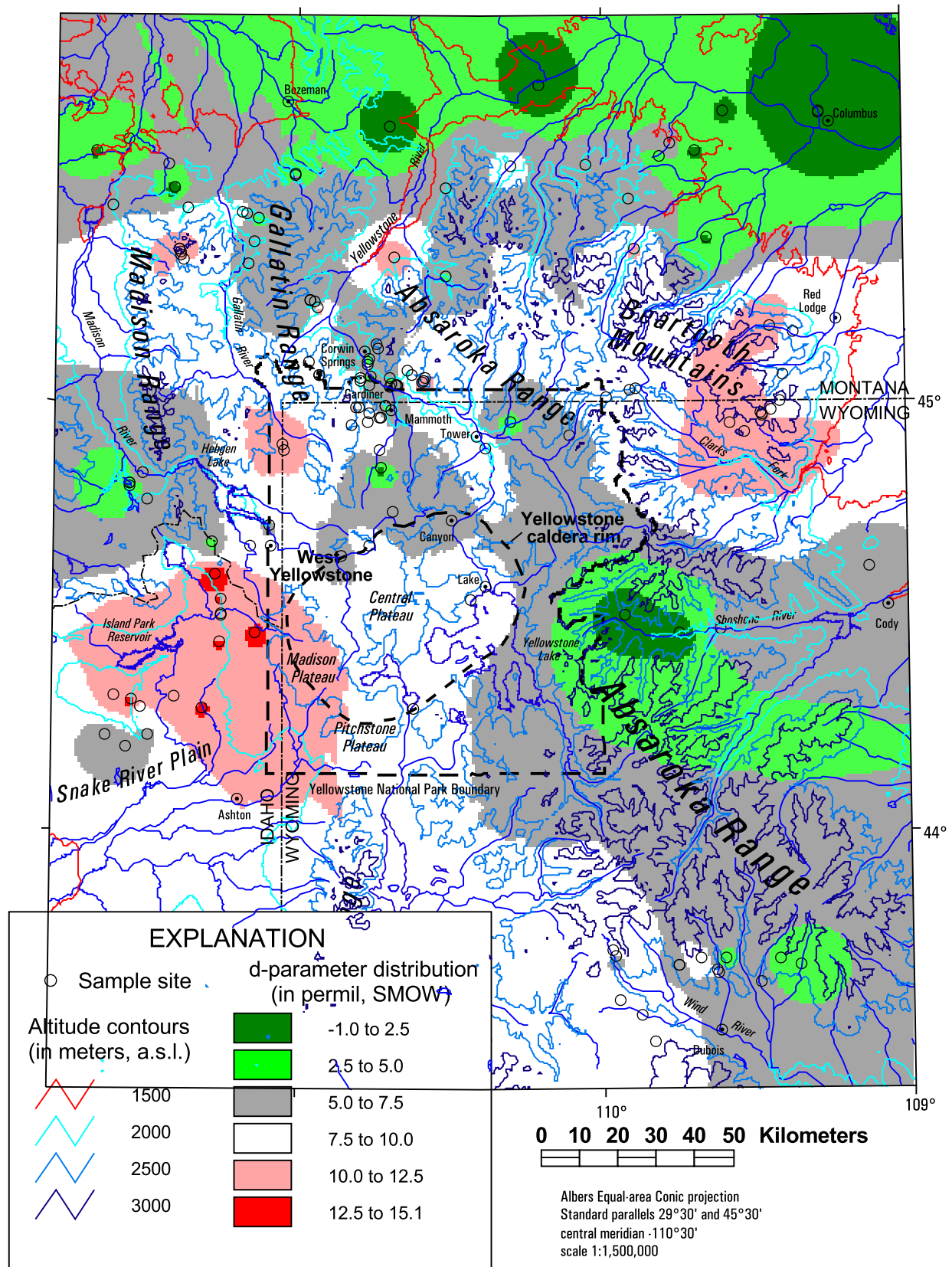


Figure 15. d-parameter distribution for cold waters in the study area.

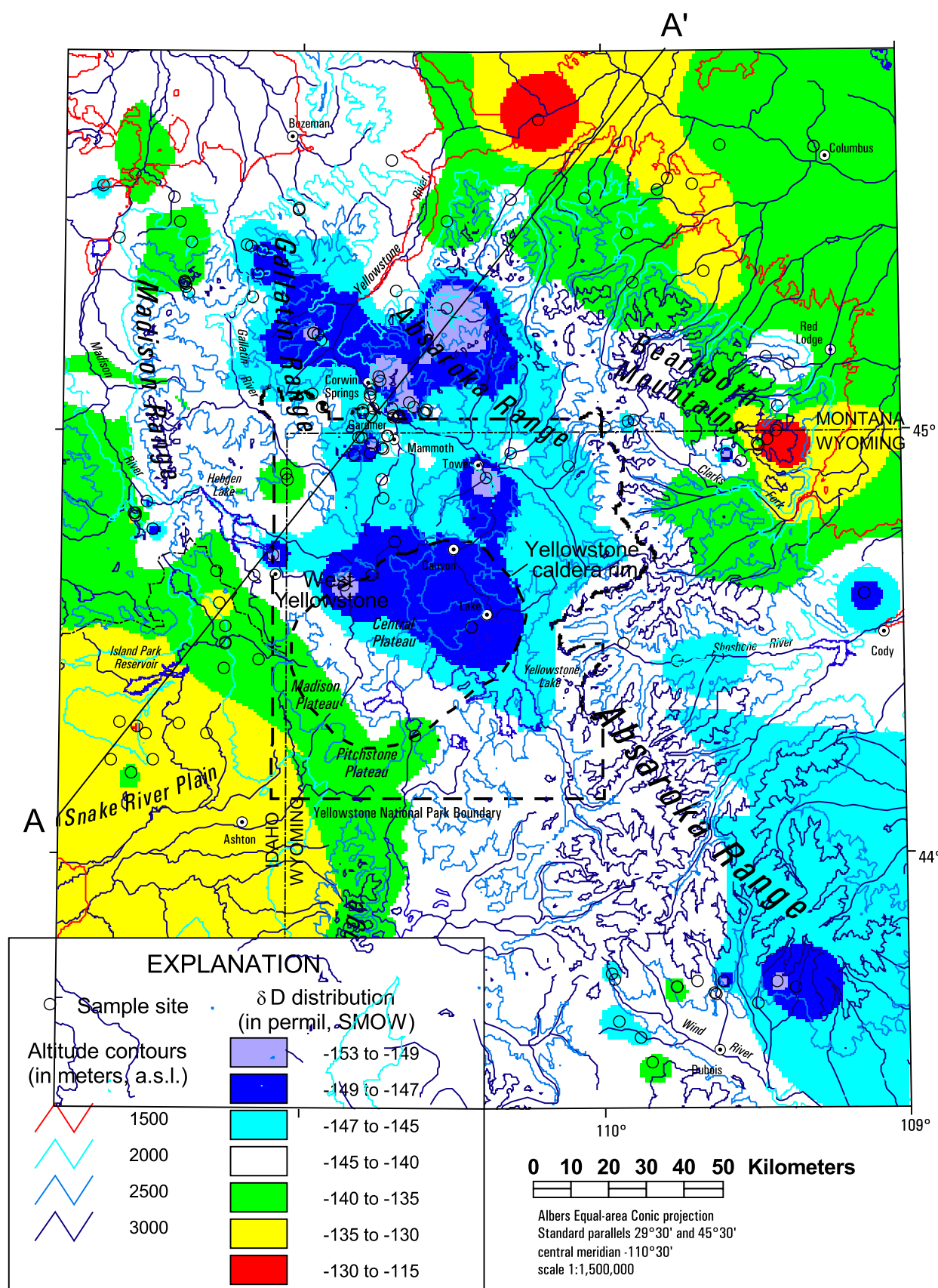


Figure 16. δD distribution for cold waters in the study area. Line A-A' is traverse in figure 19.

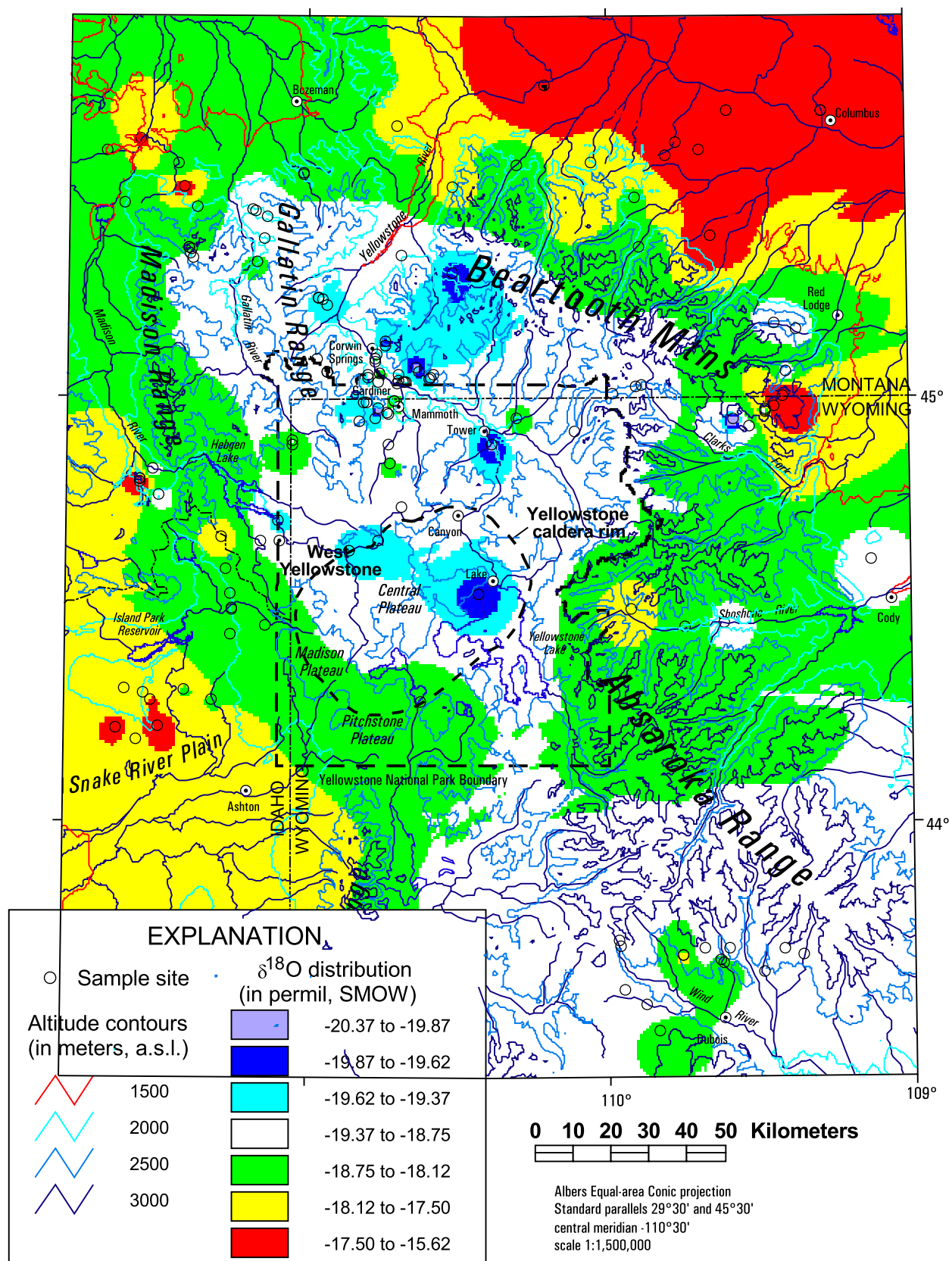


Figure 17. $\delta^{18}\text{O}$ distribution for cold waters in the study area.

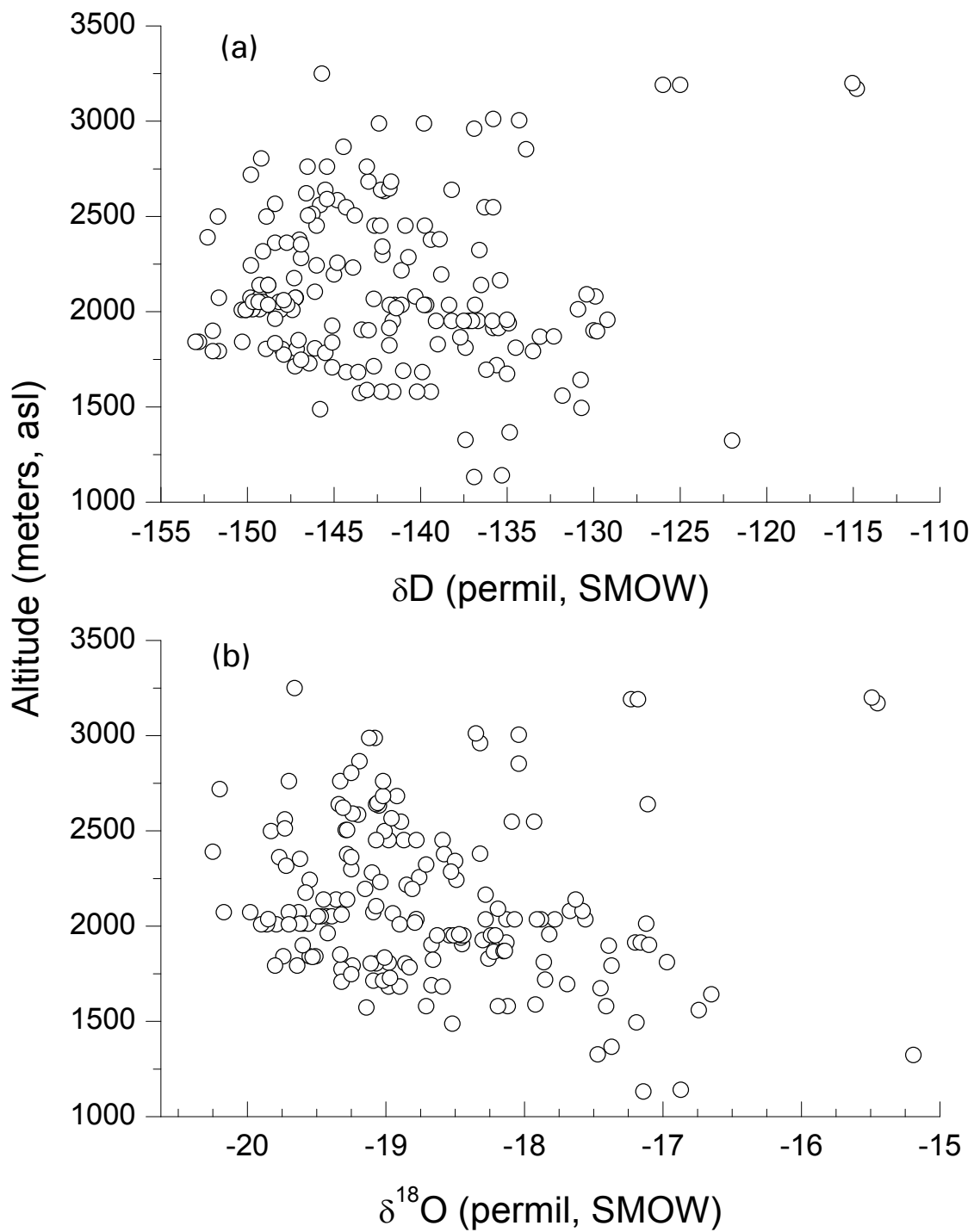


Figure 18. Scatter plot of altitude vs. δD and $\delta^{18}O$ values for cold-water samples in the study area. Note the large scatter in the data points indicating complex relationship between altitude and water isotopes.

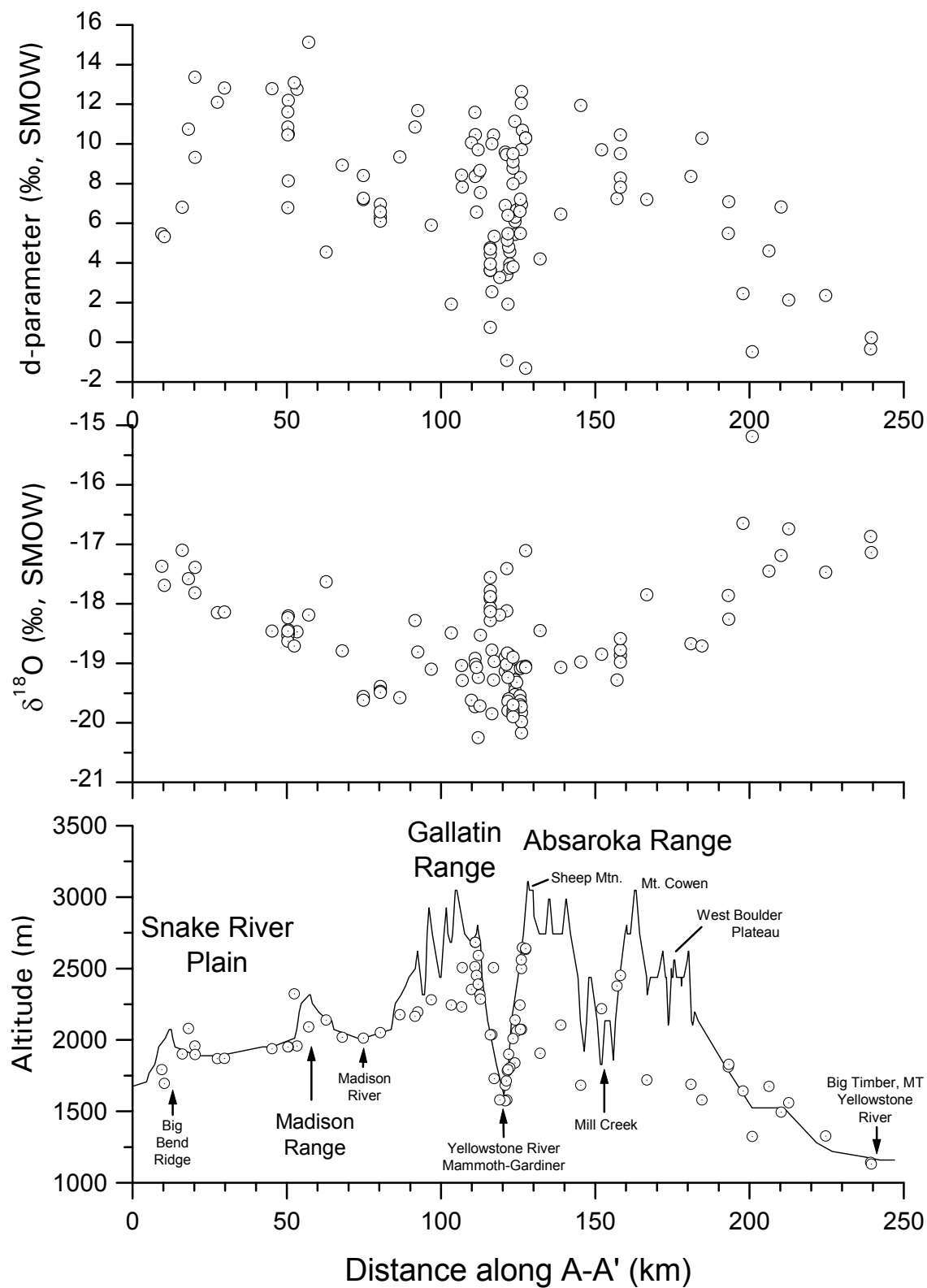


Figure 19. Cross section through study area showing altitude of sample sites, and δD and d -parameter values of cold-water samples vs. distance along line A-A' (fig. 16).

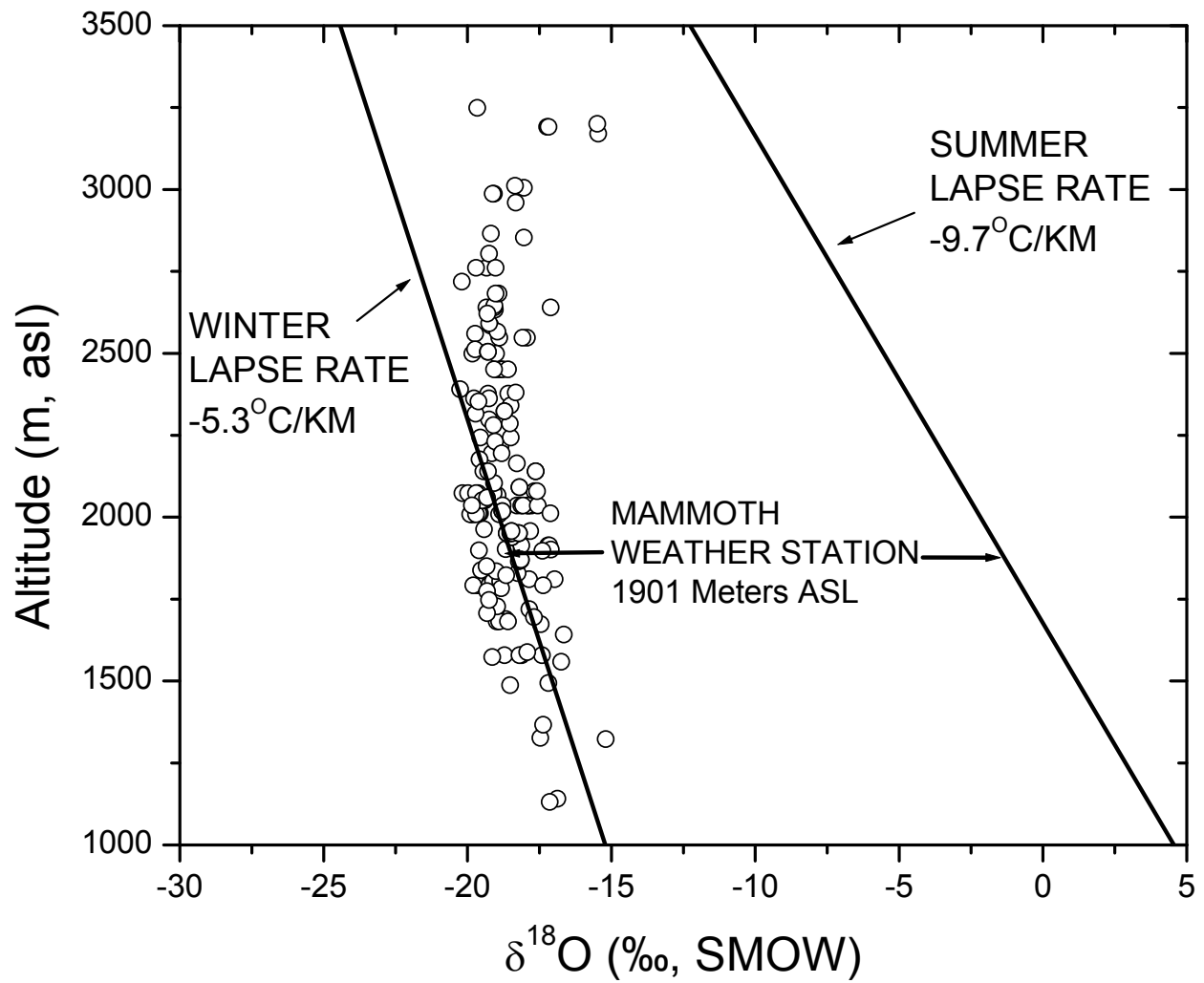


Figure 20. Scatter plot of altitude vs. $\delta^{18}\text{O}$ values for cold-water samples in the study area, compared to the predicted $\delta^{18}\text{O}$ values for winter and summer conditions at (see text for full explanation) Mammoth weather station (modified from Thordsen and others, 1992).

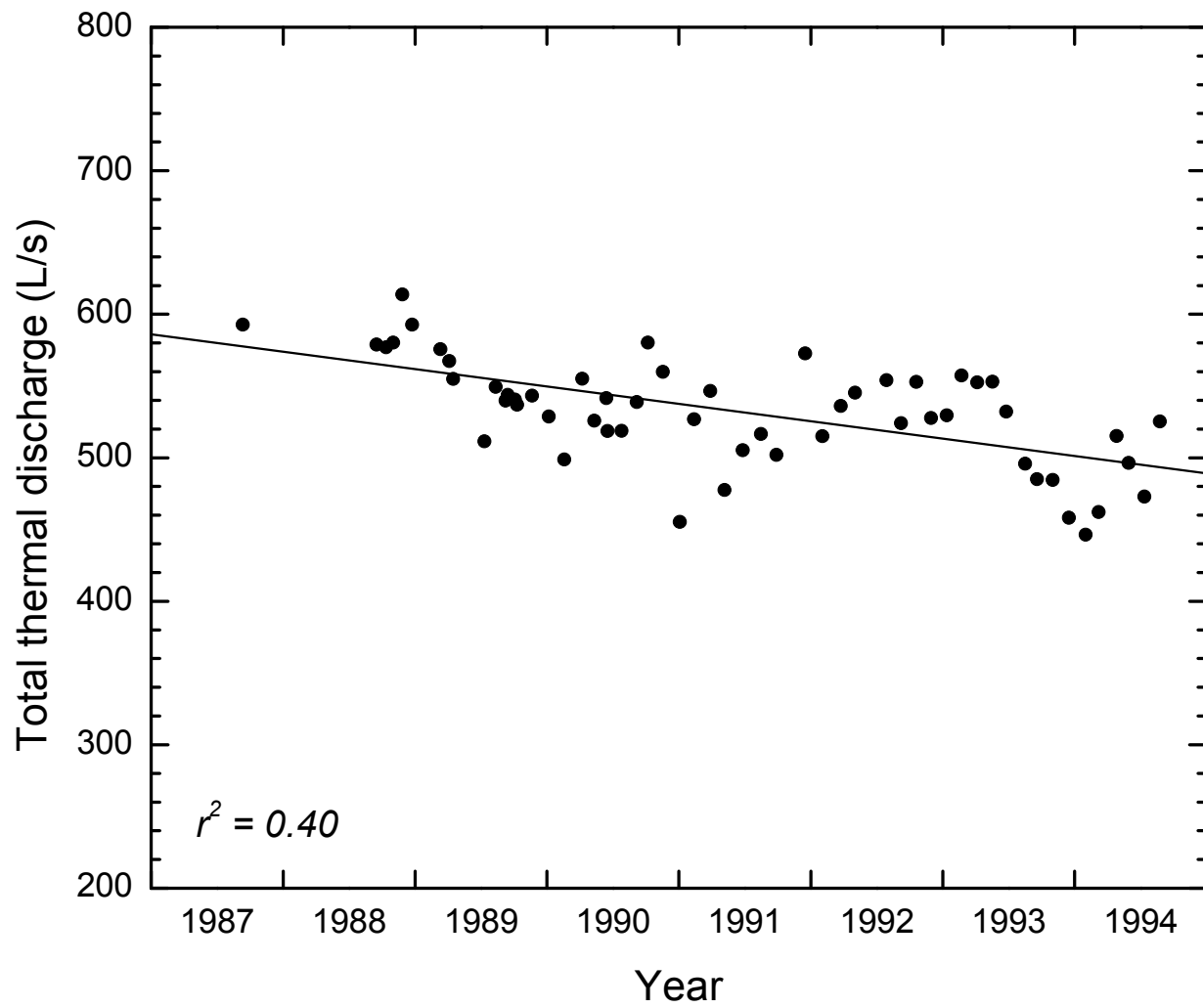


Figure 21. Total thermal water discharges from the Mammoth Hot Springs system for 1987-1994 (from Kharaka and others, 2000).

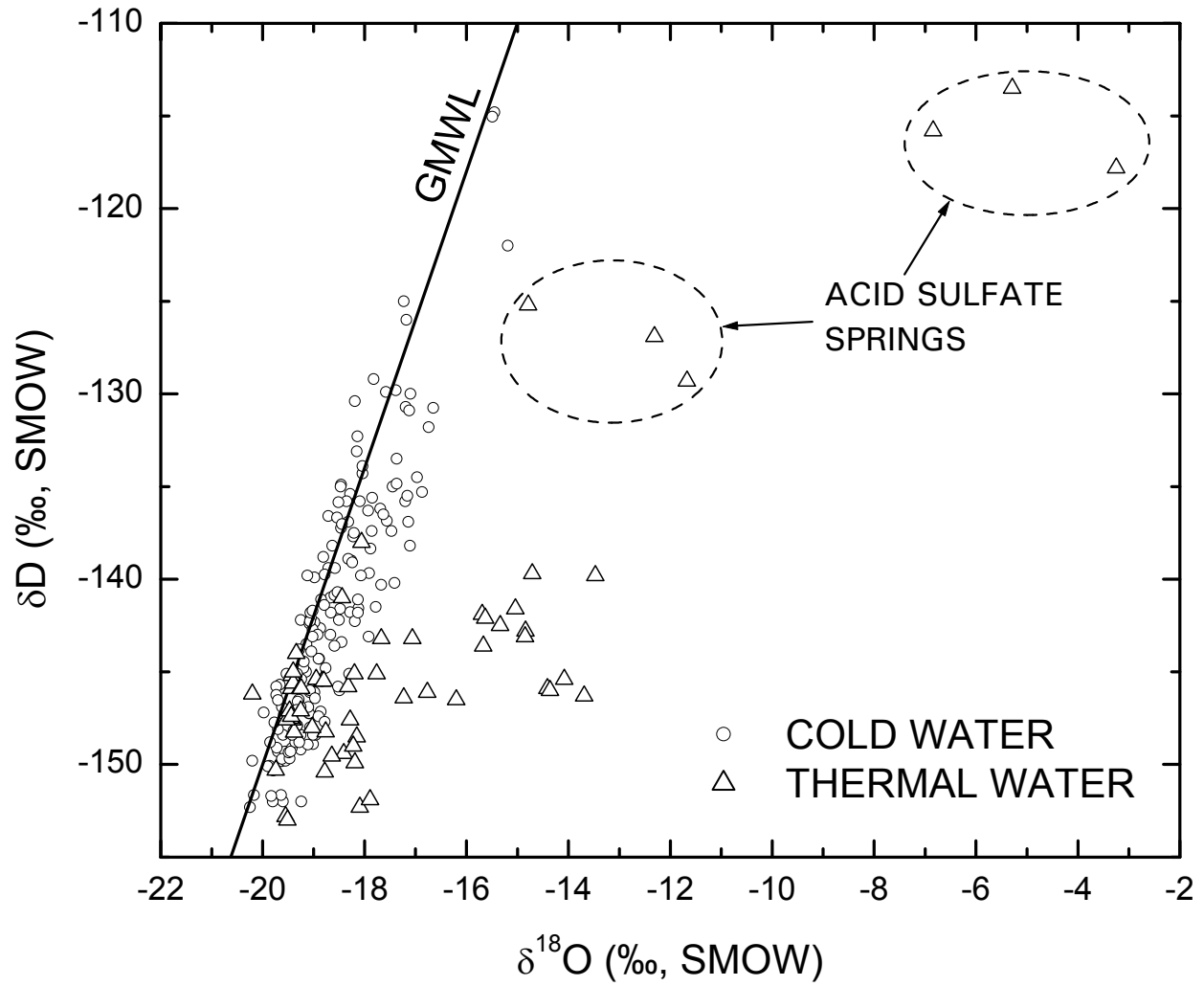


Figure 22. Scatter plot of δD vs. $\delta^{18}O$ values for thermal- and cold-water samples in the study area. Samples from acid sulfate springs controlled by boiling and condensation are delineated.

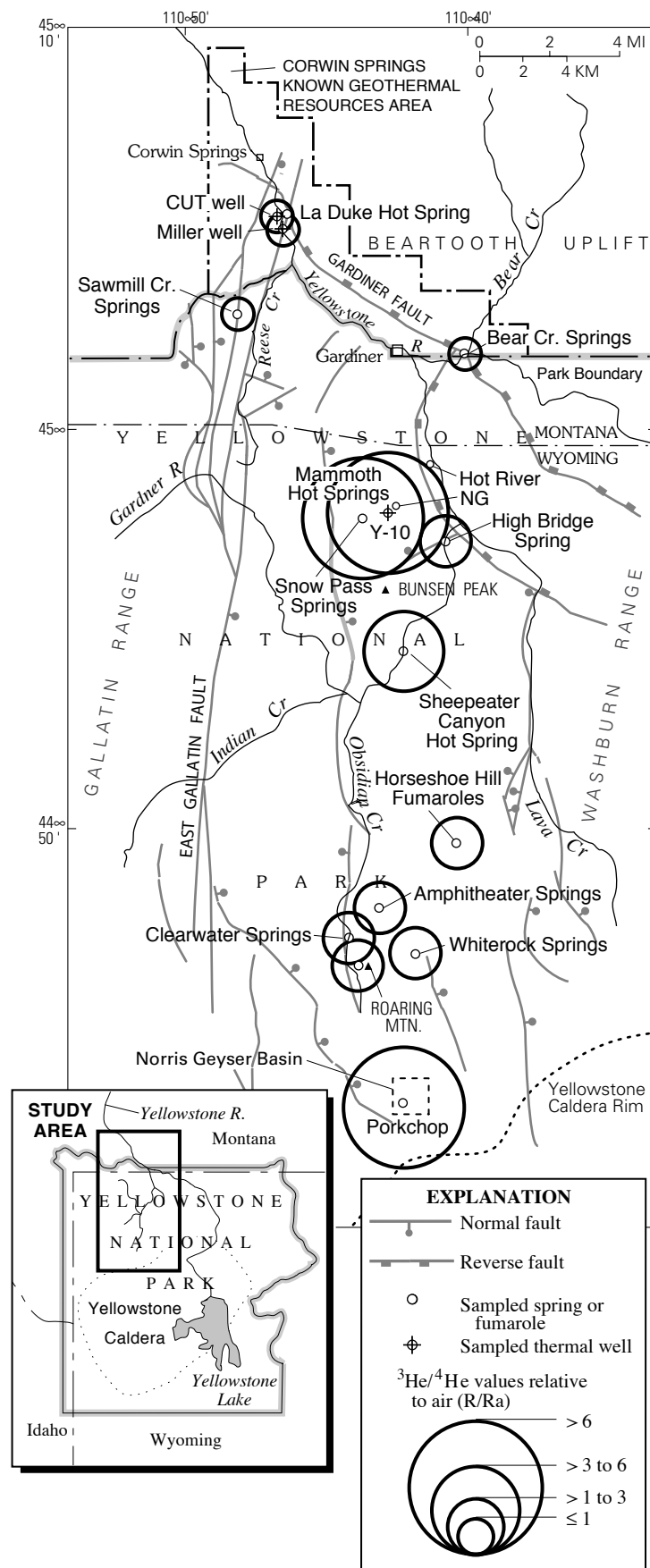


Figure 23. Distribution of the $^3\text{He}/^4\text{He}$ values relative to air (R/R_a) in thermal fluids from the Norris-Mammoth corridor. Note the high values for the Mammoth system and Norris Geyser Basin and the relatively low values in the intervening thermal areas (from Kharaka and others, 2000).